Tenability Analysis of Television Fires in a Sprinkler Protected Compartment

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Abstract

Unwanted smoke detector activation is an increasing problem in New Zealand, particularly in multi-storey apartment buildings. Many of these building are designed for the accommodation of tertiary students, and will generally have very small living areas combined with a kitchenette. The deemed to satisfy provisions of the building code require smoke detection in the means of escape within a household unit. In most multi-storey apartment buildings there is only one way out of the apartment and this is usually through the living area, therefore smoke detection must be included in this area. The small size of this space however means that cooking fumes are a frequent source of unwanted smoke detector activation.

One proposed solution to this problem is to remove the smoke detection from the living area, and rely on a fast response residential sprinkler system to provide sufficient early warning in the event of fire. The purpose of this study was to evaluate whether the warning provided by a fast response residential sprinkler system would be adequate to allow occupants to safely escape from an apartment in the event of a fire. The scenario selected for the evaluation involved a television fire in the living room, with the occupant asleep in an adjacent bedroom and the connecting door between the two rooms closed. Previous live fire demonstrations by the New Zealand Fire Service indicated that burning televisions can produce significant quantities of smoke at relatively low heat release rates. It was considered that the low heat release rate would challenge the response capability of the sprinkler head, and that the large quantity of smoke would present a serious threat to the occupant attempting to escape through the living area.

The performance of the sprinkler system was assessed against that of an optical smoke detector and an ionisation smoke detector. These smoke detectors represent the level of safety required by the deemed to satisfy provisions of the building code. At the same time the performance of alternative detection systems including CO and heat was also be explored, along with the reaction time of smoke detectors in the spaces adjoining the living room (since the proposal is only to remove smoke detection from the living area).

The evaluation was conducted in a full scale gypsum plasterboard lined compartment measuring 8 m x 4 m x 2.4 m high. A 1.2 m^2 lobby was used to represent an adjoining room and a standard hollow core door connected the two spaces. The compartment was fitted with two pendent mounted fast response residential sprinkler heads, and the televisions were located in one corner of the compartment. The television sets were selected at random from electrical servicing stores that had deemed them irreparable. A series of 21 tests was conducted during the evaluation, using a tea light candle against the outside of the television casing as the ignition source. Gas analysis for CO, CO_2, O_2, HCN and HCl was carried out during the tests, along with measurements of visual obscuration, compartment temperature and mass loss of the fuel. The response times of each detection system was also recorded.

Tenability conditions within the compartment were determined using fractional effective dose (FED) calculations, and these were assessed against the alert times provided by the various detection systems to produce an available escape time. Visual obscuration measurements were used to estimate occupant movement speed through the compartment to provide a required escape time. This was compared to the available escape time provided by each detection system to determine whether the occupant could safely escape from the apartment. The results showed that the sprinkler system did not respond well to the television fires. On a number of occasions the sprinkler system did not operate at all and the TV set burned out completely. When the sprinkler system was used to provide warning, the required escape time exceeded the available escape time in 5 out of the 21 cases. In another 6 cases the margin provided by the available escape time was less than two minutes. The study therefore concluded that the fast response residential sprinkler system did not provide a sufficient level of safety to allow an occupant to escape from the apartment under this fire scenario. The results revealed that all the other detection systems provided available escapes that exceeded the required escape times, although the margins were generally less than 3 minutes in the case of the thermal detector and the two lobby detectors. Of all the systems evaluated, only the CO detector achieved an equivalent level of safety to the smoke detectors in the compartment and could therefore be considered to comply with the deemed to satisfy provisions of the building code.

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Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Background

Over the past decade there has been a distinct change in the nature of residential construction in this country. Traditionally as a nation, New Zealand has deemed the residential dwelling to be the exclusive domain of the stand-alone house or block of low rise flats. Lately however the rapid influx of international students to the major centres has seen a dramatic increase in the number of high rise apartment buildings. New Zealand has aggressively marketed itself overseas, particularly in Asia, as an ideal country for young people to study English as a second language in a safe and inexpensive environment. This marketing strategy has led to an explosion of English language schools located within the central business district (CBD) of Auckland, and to a lesser extent Christchurch and Wellington.

The natural inclination of the international students to live in close proximity to their place of study, coupled with an affinity for inner city living unfamiliar to most New Zealanders, has led to a corresponding boom in high rise apartment development. The price and scarcity of land in the CBD area along with the drive to provide cost effective accommodation has seen both the building footprint and apartment floor area drastically reduced in comparison to traditional residential accommodation. This design philosophy has been possible due in part to the lifestyle expectations of the inner city dwellers who tend not to spend excessive amounts of time in their apartments, choosing instead to dine out and socialise in communal areas rather than in their homes. This attitude is certainly facilitated by the expectations of the foreign student market, the majority of who are accustomed to living in small apartments in densely populated cities.

While the multi-storey apartment market has been driven primarily by the need to accommodate international students, the idea of inner city living has taken on an appeal to many New Zealanders as well. For some the incentive is to avoid a long commute from their city workplace, while others do not have the time or inclination to maintain a house and land. Many are attracted by the promise of a vibrant urban lifestyle, and some simply cannot afford to own a free standing house within the surrounding suburbs. Whatever the reason, multi-storey apartment living is now a genuine dwelling option for a substantial segment of the population. Those that take this option have chosen to trade off living space in favour of the advantages apartment living offers.

While the changing face of urban accommodation has arguably enhanced the inner city environment, it has also brought with it certain life safety issues that have not previously been encountered in any depth in this country. The drive to provide a large number of inexpensive apartments within a small building footprint has resulted in some less than desirable outcomes from a fire safety perspective. The first consequence of this design philosophy is that there is only one way out of the apartment (see Figure 1.1.1). This immediately restricts the options available to an occupant attempting to escape in the event of a fire occurring within the apartment. A reduction in the number of egress routes therefore necessitates an increase in the available time to escape. This requires the presence of an early warning system to ensure that the only available escape route is not compromised by fire or smoke before an occupant can safely evacuate the apartment. This fact has been recognised by building regulators, who have mandated the use of early warning in escape routes in the deemed to satisfy provisions of the building code [1].

One of the most common and effective forms of early warning in the event of fire is smoke detection. However the premium placed on floor space means that hallways within apartments are avoided, and so the escape route is invariably through the living area, which proves problematic with regard to smoke detection. The standard apartment design incorporates the kitchen into the living area, and the small size of this living area makes it difficult to position a smoke detector in a location that will not be effected by cooking fumes. This problem is frequently exacerbated by inadequate ventilation in the apartment, and the cooking area in particular. As part of cost reduction measures, kitchen range hoods in multi-storey apartments are most commonly recirculating types, as this means that expensive ducting can be avoided.

Unfortunately the filtering system on these range hoods is generally incapable of preventing cooking fumes from activating a smoke detector located in the living area. The net result is a high incidence of unwanted smoke detector activation caused by normal cooking activities. As a consequence, apartment occupants naturally develop an air of complacency regarding fire alarm activation, which is a potentially serious problem in the event of a genuine emergency. If smoke detector activation within an apartment generates a building wide evacuation, all the occupants of the building will be subjected to substantial inconvenience.

Typical multi-storey apartment building

Typical 2 bedroom apartment floor plan

Figure 1.1.1: Examples of inner city multi-storey apartment buildings

Another common response to the frequent unwanted alarms is for the occupants to tamper with the smoke detector head. As the majority of systems in modern multi-storey apartment buildings are analogue addressable, removing the detector head will generate a fault in the system and identify the apartment in question. Occupants have instead resorted to covering up the detector heads in the living areas, for example by taping a plastic bag over them. While this will stop the unwanted alarms, it also renders the early warning in the escape route ineffective. A final consequence of unwanted alarms in buildings with a Fire Service connected smoke detection system is the charges incurred for the call out of the Fire Service and the alarm agent. Call out fees for alarm agent attendance to unwanted activations can become so great that the building owner or body corporate refuse to continuing paying, in which case the alarm agent will cease attending, and fire alarm system may remain out of action.

A number of solutions have been offered to this problem of unwanted smoke detector activations. These include making the detectors in the apartments local sounding only. This will prevent a building wide evacuation, and the call out of the Fire Service and alarm agent. Providing hush buttons in an easily accessible position to temporarily mute the sounder is another possible method of mitigating the effects of an unwanted activation. Unfortunately neither of these options will reduce the number of unwanted activations. Improving the quality of the ventilation within the apartment, and the quality of the smoke detection system, will help reduce the number of unwanted activations, however both these solutions come with significant cost implications.

There is another solution that has been proposed, and this option forms the basis for the analysis contained in this report. The majority of multi-storey apartment buildings are required to have sprinkler protection as part of the fire safety provisions. In recent years the use of fast response residential sprinkler systems has become commonplace. Fast response residential sprinkler heads, as the name suggests, are designed to activate more rapidly than conventional sprinkler heads, thereby providing a greater degree of protection to high risk spaces, such as those containing sleeping occupancies.

The solution therefore proposes to remove smoke detection from the living area in the apartment and rely on the fast response residential sprinkler system to provide adequate early warning in the event of fire. The supposition is that a fast response residential sprinkler head will react in time to prevent the escape route from becoming compromised to the extent that the occupants are unable to safely evacuate.

This proposal has a number of advantages. Since sprinkler heads are activated by heat rather than smoke, it would virtually eliminate the incidence of unwanted alarms caused by cooking, or any other normal household activities. As the sprinkler system is required in the majority of apartment buildings anyway, there would be significant cost savings by not having to provide a smoke detection system within the living areas of the apartments. If the concept of removing smoke detection is extended to the entire apartment, including the bedroom/s, even greater initial cost reductions could be made, and additional savings would result from avoiding the ongoing maintenance regime required by the smoke detection system. This is a particular problem in buildings with individually owned apartments where gaining access to carry out scheduled servicing is often difficult.

The obvious benefits make this option particularly attractive, however there are a number of issues that must be examined before its validity can be ascertained. The most fundamental question is whether a sprinkler system can in fact provide the same level of protection as a smoke detection system. This is not an easy question to answer at face value. For a start smoke detectors and sprinklers are designed to perform different roles, and consequently operate in different ways. A smoke detector is designed to detect a small quantity of combustion product in the atmosphere, whereas a sprinkler operates in response to the heat produced by a fire. So while a smoke detector is capable of detecting the presence of a fire at a very early stage, often before flaming combustion occurs, a sprinkler requires the presence of a fairly well established fire before sufficient heat is generated to activate the head. An initial assumption is therefore that a smoke detector will activate before a sprinkler under normal circumstances. On the other hand the operation of a sprinkler head will not only sound the alarm, it will also control the development of the fire and prevent it from spreading. In many instances it will extinguish the fire completely.

So when comparing the two systems, one must assess whether earlier warning on its own is more beneficial than delayed warning coupled with fire control. Certainly in terms of reducing the threat of fire to the rest of the building's occupants, preventing the fire from spreading is the best option. However since the proposal relates to the removal of smoke detection required under the building code, the assessment criteria needs to be in terms of the functional role of the smoke detector, i.e. to ensure the occupants have sufficient time to evacuate the apartment safely. The issues that need to be addressed when making this assessment include the time difference between smoke detector activation and sprinkler activation, the tenability within the escape route at the time of activation (for both the smoke detection and sprinkler operation), and the effect of sprinkler activation on the tenability conditions within the escape route. Since a sprinkler head, unlike a smoke detector, is reliant on heat to operate, an obvious area on which to focus the assessment would be a smouldering fire, or a flaming fire that produces little heat.

During live fire demonstrations conducted by the New Zealand Fire Service at Long Bay, Auckland in February 2003, it was observed that fires involving burning television sets and computer monitors produced significant quantities of heavy smoke before generating sufficient heat to operate a fast response residential sprinkler system. The demonstrations appeared to indicate that the safety of any occupants within the building would have been in jeopardy prior to sprinkler activation. As the fires were designed for demonstration purposes rather than to gather experimental data, these observations were not substantiated. Nevertheless, it was considered that this scenario would prove particularly challenging for a sprinkler system tasked with providing early warning as well as fire control.

1.2. Objective

The aim of this study was to evaluate whether the warning provided by a fast response residential sprinkler system would be adequate to allow occupants to safely escape from the apartment in the event of a fire in the living room. A television fire was selected for the evaluation as previous live fire demonstrations by the New Zealand Fire Service had indicated that burning televisions can produce significant quantities of smoke at relatively low heat release rates. It was considered that the low heat release rate would challenge the response capability of the sprinkler head, and that the large quantity of smoke would present a serious threat to the occupant attempting to escape through the living area.

The performance of the sprinkler system would be assessed against that of an optical and an ionisation detector, as these smoke detectors represent the level of safety required by the deemed to satisfy provisions of the building code [1]. At the same time the performance of alternative detection systems including carbon monoxide (CO) and heat would also be explored, along with the reaction time of smoke detectors that were presumed to be present in the spaces adjoining the living room.

1.3. Methodology

The scenario assumed for the analysis is that an occupant is asleep in a bedroom, and a fire has developed in a television set in the living room of the apartment. The occupant must be alerted to the fire by the fire safety system in the apartment, and must evacuate the apartment safely via the living room (i.e. through the enclosure of fire origin). Four different fire safety systems were evaluated in the tests. They represent the potential ways in which warning of fire could be achieved within the apartment.

1. Smoke detection installed in the living room – this is a prescriptive requirement under the building code when the living room forms part of the escape route.

2. Smoke detection installed in space adjacent to the living room – this represents the smoke detectors that would normally be installed in the bedroom/s of the apartment and could provide the first indication of fire if smoke detectors have been removed from the living room.

3. Fast response residential sprinkler system in living room – this is considered a mandatory requirement for most multi-storey residential buildings whether or not smoke detection is present in the living room or elsewhere within the apartment

4. Alternative fire detection systems - this includes carbon monoxide (CO) and thermal detectors. These alternatives might not be as sensitive to unwanted alarms as traditional smoke detection.

The methodology for conducting the analysis was as follows:

1. Construct a full-scale residential sized compartment that represents the living space of the apartment.

2. Fit out the compartment with the four fire safety systems, along with a method of measuring their performance.

3. Install instrumentation within the compartment to measure tenability conditions during the tests.

4. Carry out a series of tests involving television fires within the compartment.

5. Compare the performance of the four fire safety systems in terms of the ability of each system to detect the presence of the fire in the compartment.

6. Measure the tenability conditions within the compartment over then duration of the fire for each test.

7. Using the information on tenability conditions, assess whether the occupant would be capable of safely escaping through the compartment subsequent to warning being provided by each of the four fire safety systems.

8. Determine whether replacing smoke detection with fast response residential sprinklers affected the ability of occupants to safely evacuate the apartment in the event of fire

It is important to note that this analysis is only concerned with the ability of each fire safety system to detect the presence of fire. It assumes that an effective method of alerting the occupant/s will follow automatically once the fire has been detected. It should also be noted that the analysis does not take into account issues such as variations in the reliability of the different fire safety systems.

2. Literature Review

2.1. Toxicity

It has long been recognised that exposure to toxic combustion products presents as much of a risk in a fire as exposure to heat and flames, if not more. The impact of smoke and toxic fumes on fire victims appears to be on the increase. According to the U.K. Home Office, approximately half of all fatal casualties, and a third of all non-fatal casualties of dwelling fires were reported as "being overcome by smoke and toxic gases" [2]. In his chapter on the toxicology assessment of combustion products [3] in the Society of Fire Protection Engineers Handbook of Fire Protection Engineering (commonly referred to as the SFPE Handbook) Purser states that although there was some reduction in the overall number of fire deaths in the United Kingdom during the 1990s, smoke deaths were running at approximately four times the levels recorded during the 1950s. Injuries in the United Kingdom from smoke and toxic fumes have also increased six fold. In the United States smoke inhalation accounted for nearly three-fourths of fire related deaths in 1992, up from less than three-fifths in 1979 [4].

Combustion toxicology is an extremely complex field of study. The decomposition and burning of even a single and relatively simple organic polymer may produce literally hundreds of different airborne chemicals in the atmosphere with the types and concentrations changing throughout the fire [5]. This view is reinforced in Purser's chapter in the SFPE Handbook, which states that the atmospheres of thermal decomposition products, even for single materials, contained large numbers of potentially toxic products. The chemical composition of the products could vary considerably depending on the different conditions of temperature and oxygen supply under which they were decomposed. In other words, smoke toxicity is not a fundamental property of the material being burned, and it could be argued that the results of material toxicity tests could be irrelevant to real life fires [6]. Nevertheless, studies have consistently identified a relatively small number of key substances as being critical to toxicity assessments.

Purser cites the results of chemical studies of large-scale and small-scale experimental fires and animal exposures to the thermal decomposition products of a wide range of materials in identifying that toxicity is dominated either by an asphyxiant gas (carbon monoxide or hydrogen cyanide) or by irritants (such as hydrogen chloride and acrolein). An asphyxiant is a toxicant causing hypoxia (a decrease in the oxygen supplied to or utilised by body tissue), resulting in central nervous system depression with loss of consciousness and ultimately death [7]. In contrast to the direct effects of asphyxiant toxicants, the effects of exposure to irritants are much more complex. Consequently it is difficult to relate irritant concentrations quantitatively to their impact on ability to escape safely. Most fire effluent irritants produce signs and symptoms of both sensory/upper respiratory tract and pulmonary irritation [7].

Of the various asphyxiant and irritant combustion products, Purser considers carbon monoxide to present the greatest toxic hazard. Further publications support Purser's view that carbon monoxide (CO) is the dominant toxic fire product. Babrauskas states that carbon monoxide accounts for roughly half of the fire toxicity problem [8]. While CO is not greatly toxic in comparison to other substances, it is considered the primary agent due to its copious generation by all fires. In a paper on evaluating toxic hazard, Hartzell [9] also considers CO to be the major threat in most fire atmospheres, for the same reasons as Babrauskas.

CO derives its toxicity from its ability to bind up to 300 times more strongly to haemoglobin in the blood than oxygen can [10]. This results in an accumulation of the adduct, carboxyhaemoglobin (COHb), in the bloodstream and in a consequent reduction in the oxygen-carrying capacity of the blood. Hydrogen cyanide (HCN) is a very rapidly acting toxicant that is approximately 20 times more toxic than carbon monoxide [9]. It does not combine appreciably with haemoglobin, but does bind with the enzyme oxidase in body cells. The result is inhibition of the utilisation of oxygen by the cells (cytotoxic hypoxia).

In the late 1970s research was carried out by Berl and Halpin of John Hopkins University into carbon monoxide poisoning in fires [11]. The study was based on an analysis of 463 fire deaths in Maryland and found that 48 percent of fatalities could be attributed to CO alone, with another 26 percent attributed to significant carbon monoxide in combination with one or more other toxins or other factors. 30 percent COHb was used as a figure to indicate significant carbon monoxide contribution to death and 50 percent COHb as sufficient to cause death due to carbon monoxide alone. The research also indicated that no deaths could be attributed solely to toxicants other than carbon monoxide, and that at most only one-fourth of the deaths involved other toxicants, even as contributing factors.

Harland and Anderson from the University of Glasgow studied 227 fire deaths from 1976 to 1981 in the Glasgow area and found that 54 percent of the deaths were assumed to be from carbon monoxide poisoning [10]. The threshold for fatal carbon monoxide poisoning was assumed to be 50 percent COHb. The study also found that of the cases in which cyanide measurements were available, 24 percent were in the range likely to produce significant toxic effects, however only 5 percent had potentially fatal cyanide concentrations. Significant but non-fatal toxic effects from cyanide were considered to occur in the region of 50μmol/l, whereas 100 μmol/l was assumed to be the threshold for serious risk to life.

A retrospective analysis of records kept by the New Jersey State Medical Examiners Office is reported in a paper by Nelson [12]. This study looked at 433 fire fatalities from 1985 to 1987. COHb levels averaged 45 percent, and exceeded 50 percent in 195 cases. Blood cyanide data (taken from 364 victims) averaged 1.0 mg/l, and exceeded 3 mg/l in 31 cases – a value taken by some to be lethal. However in these latter cases the mean COHb level was 62.5 percent, also a lethal level. Only 8 of the 31 victims had COHb levels at less than 50 percent. It is worth noting that in his study, Nelson references a 1991 paper by Yoshida et al, published in *Forensic Science International*, in which an analysis of Japanese data found that cases of fatal HCN poisoning are rare.

Apart from the asphyxiant gases, the other major toxic component of smoke is the irritant gases. According to Purser the physiological effects of exposure to irritant combustion products such as hydrogen chloride result in varying degrees of incapacitation which may also lead to death or permanent injury. Some of the effects include impaired vision resulting from the painful effects of irritant smoke products on the eyes, respiratory tract pain and breathing difficulties or even respiratory tract injury resulting from the inhalation of irritant smoke. In extreme cases this can lead to collapse within a few minutes from asphyxia due to laryngeal spasm and/or bronchoconstriction. Lung inflammation may also occur, usually after some hours, which can also lead to varying degrees of respiratory distress.

The effects of irritants produced in fires are considerably harder to quantify than those of the asphyxiant gases. For a start it is more difficult to conduct post mortem assessments of irritant levels within the body, since they do not directly effect the central nervous system. Even if the exposure level is known, accurately assessing the effects is still difficult. For example, Hartzell [13] explains that although eye and upper respiratory tract irritation are certainly painful, it is unclear whether or not such effects would be incapacitating in a physiological sense. According to Purser [3] there are two distinct ways in which irritants produce incapacitation. One is pain caused by sensory irritation, which effects the eyes and upper respiratory tract and to a lesser extent the lungs, and the other is acute pulmonary irritant response. This consists of edema and inflammation that may lead to death 6 to 24 hours after exposure.

While Purser believes that the pain caused by sensory irritation can in itself prove incapacitating, he admits that the severity appears to depend largely on the type of smoke. He states that fire victim reports indicate that smoke from a well ventilated fire burning cellulosic materials is irritating but not incapacitating, whereas smoke from burning plastics (e.g. from a car fire) was found to cause severe effects when only a small amount was inhaled. Purser concludes that it is likely that irritant smoke products do have some severe effects on the escape capability of fire victims, but it is difficult at present to predict accurately the likely degree of incapacitation.

2.2. Tenability Analysis

The following discussion on tenability analysis is closely based on the content of Purser's chapter on toxicity assessment contained in the SFPE Handbook [3]. The intention is to provide an overview of Purser's work as it pertains to this study. For more comprehensive coverage on the topic of tenability analysis, Purser's chapter should be consulted directly.

Purser regards the major considerations when conducting a hazard assessment based on tenability limits to be:

1. The time when partially incapacitating effects are likely to occur which may delay escape.

2. The time when incapacitating effects are likely to occur which might prevent escape, compared with the time required for escape.

3. Whether exposure is likely to result in permanent injury or death.

It is important to make some estimate of the effects that are likely to delay escape, which in turn may prevent occupants from escaping during the time available before conditions becoming so bad that they are no longer capable of escaping. The event most likely to delay an escape attempt is exposure to optically dense and irritant smoke, which tends to be the first hazard confronting fire victims. If conditions are severe enough, a moment may be reached when incapacitation is predicted to be sufficiently bad as to prevent escape entirely. For some forms of incapacitation, such as when asphyxia leads to a rapid change from near normality to loss of consciousness, this moment is relatively easy to define. For other effects a defining moment is less easily characterised; for example when smoke becomes so irritant that pain and breathing difficulties lead to a cessation of effective escape attempts. Nevertheless it is considered important to attempt some estimate of the moment when conditions become so severe in terms of these hazards that effective escape attempts are likely to cease, and when occupants are likely to suffer severe incapacitation, injury or death. Time to incapacitation (of one degree or another) is in reality more important than time to death because most fires are potentially lethal due to CO or heat if the victim is exposed to these for sufficient time. Therefore the two major determinants as to whether a victim escapes are the point at which incapacitation by toxic products is reached, and how these products affect escape capabilities during the window of time available between being alerted to the fire and the development of lethal conditions.

The majority of work done on calculating tenability limits in humans is based on animal experiments. The most common animals used in these tests are rodents, although primates have also been used in some tests. The standard method for assessing the toxicity of materials using animal experiments is the LC_{50}. The LC_{50} is described as the concentration of combustion products expressed in terms of mg of material per litre of air causing the deaths of 50 percent of animals exposed. The degree of toxicity is determined by the concentration of toxic product in the target organ of the body, and the time period for which a toxic concentration is maintained. In general it is not feasible to measure the amount of toxic product accumulated in the subject (i.e. carboxyhemoglobin in the blood for CO poisoning), and so the concentration of toxic product in the smoke is used to predict toxic effects. It should be noted that as this is an indirect method of estimating exposure, some degree of error or uncertainty will be involved. Relating concentration of a toxic product in the smoke to concentration within the body of the subject means that other factors such as respiration rate and particle size of aerosols play an important part in determining the ultimate degree of toxicity. Respiration affects the rate of uptake of the toxic product, and this can be estimated by measuring the volume of air breathed by the animal per minute (the respiratory minute volume, or RMV). Variations in RMV can have dramatic effects on toxicity.

The primary parameters however remain the concentration of the toxicant, and the duration of exposure, which together enable a rudimentary estimation of the dose. Thus the product of concentration and time (Ct product) gives an estimate of the dose available to the animal. It follows therefore that the LC_{50} is also a time dependant value. In general safety evaluations of chemicals for acute exposure, a standard single

4 hour exposure time is used to determine the concentration of toxic material causing the death of 50 percent of the animals during exposure or within 14 days after exposure. This is known as the 4-hr LC_{50}. In practice the effects of exposure to higher concentrations for shorter periods, or lower concentrations for a longer time may be required. One way of achieving this is by conducting more LC_{50} experiments of varying exposure durations. However Haber's rule states that the toxicity depends upon the dose accumulated, and that the product of time and concentration is a constant, such that

$$W = C \times t \qquad \textbf{(2.2.1)}$$

where

W = a constant dose, specific for any given effect

As mentioned before, inhalation toxicology is often expressed in terms of *Ct* product. In the case of the LC_{50} the effect is death of 50 percent of the animals, and so

$$W = LC \cdot t_{50} \qquad (2.2.2)$$

W is expressed in mg·min/litre (i.e. the product of the concentration and the duration of the exposure causing lethality). Equation 2.2.2 implies a linear uptake of the toxic substances with time, and this holds true for many substances where the primary target organ is the lung (e.g. lung irritant gases). Unfortunately this simple principle does have exceptions. In particular, volatile substances such as carbon monoxide are both taken up and off gassed via the lungs. In this case the rate of uptake depends on the difference between the concentration inhaled and that in the body, giving an exponential uptake so that

$$W = C\left(1 - e^{-tk}\right) \qquad (2.2.3)$$

In situations where the concentration C in the atmosphere is high with respect to the concentration in the body required to cause incapacitation or death, this exponential relationship approaches the linear Haber's rule. For short exposures to high CO concentrations, uptake is approximately linear. Results from exposure experiments using primates indicated that the subjects became unconscious when exposed to approximately 27000 ppm·min of CO at concentrations between 1000 and 8000 ppm. Therefore in such situations it is possible to use a linear model for CO uptake without incurring significant error.

For the other main asphyiant gas in smoke, hydrogen cyanide, although accumulation of a dose is one factor, the most important determinant of toxicity appears to be the rate of uptake, which in turn depends upon the concentration. Incapacitation occurs rapidly (after 2 min) at the high concentration of 180 ppm (*Ct* product 400 ppm ·min), but at lower the concentration of 100 ppm, incapacitation occurs only after approximately 20 minutes, requiring a much higher Ct product dose (2000 ppm ·min).

Some toxic effects however are not dependant on a dose acquired over a period of time at all, but are purely concentration related. The irritant effects of smoke products on the eyes and upper respiratory tract (sensory irritation) occur immediately upon exposure, with severity depending upon the exposure concentration. According to Purser, increasing exposure time may even lessen the effects, as the subject adapts to the painful stimulus even though the dose is increasing. Other cases where concentration is an important determinant of toxicity as well as duration of exposure are the asphyxiant effects of hypoxic hypoxia (lack of oxygen) and hypercapnia (high carbon dioxide concentrations). If a subject is suddenly exposed to a low oxygen concentration, a finite time is required for the air in the lungs and gases in the blood to equilibrate to the new conditions. In this respect in might be argued that a "dose" of hypoxia is in fact acquired over a period of time. Once equilibrium has been established however, usually within a few minutes, the severity of the effects depends upon the oxygen concentration and does not then change appreciably with time. This also applies to high carbon dioxide (CO_2) concentrations. Equilibrium is established within a few minutes and concentration related effects then determine the pattern of toxicity. It is important to note that CO_2 is not toxic at concentrations of up to 5 percent, however it does stimulate breathing. At 3 percent CO_2 the RMV is approximately doubled, and at 5 percent tripled. This hyperventilation can increase the rate at which other toxic gases such as CO are taken up.

In attempting to predict what will happen to a subject exposed to a smoke atmosphere containing all these products it is therefore important to allow for these different concentration/time/effect relationships. In order to determine when a victim of fire exposure reaches a tenability limit (i.e. an incapacitating or lethal dose) it is first necessary to determine how much of a toxic dose the subject has received. This can be achieved by integrating the area under the fire profile curve for the toxicant under consideration. When the integral is equal to the toxic dose, the victim can be assumed to have received a dose capable of producing that toxic effect. A practical method for making this calculation is the concept of the Fractional Effective Dose (FED). The *Ct* product doses for small periods of time during the fire are divided by the *Ct* product dose causing the toxic effect. These fractional effective doses are then summed during the exposure until the fraction reaches unity, when the toxic effect is predicted to occur. The FED is therefore expressed in the following equation:

$$\text{FED} = \frac{\text{dose received at time } (t)}{\text{effective } Ct \text{ dose to cause incapacitation or death}} \qquad (2.2.4)$$

For substances obeying Haber's rule the denominator of the equation is a constant for any particular toxic effect. For substances deviating from Haber's rule the denominator for each time segment during the fire is the *Ct* product dose at which incapacitation or death would occur at the actual concentration calculated for that time segment. The denominator is usually presented in the form of equations giving the required *Ct* product doses predicted for humans, which have been derived for each toxic gas. Depending on the toxic effect sought, the fractional dose can also be expressed as the fractional incapacitating dose (FID) or the fractional lethal dose (FLD).

In a fire, exposure will not be confined to any one toxicant, but rather will involve exposure to a variety of substances at varying concentrations. Thus the interaction between the individual substances is an important consideration in the tenability assessment. Purser proposes that the interactions should be quantified in the incapacitation model as follows:

1. CO and HCN are directly additive (1:1) on a fractional dose basis (the evidence suggests that while they are additive, the additive interaction may actually be less than unity).

2. The rates of uptake of CO and HCN and their fractional doses are increased in proportion to any increase in ventilation (RMV) caused by carbon dioxide.

3. The fractional doses of CO and HCN, adapted for carbon dioxide, are additive with the fractional dose of low-oxygen hypoxia.

4. Asphyxia by carbon dioxide is independent of that induced by CO, HCN, and hypoxia.

5. Irritancy is independent of asphyxia, but uptake of irritants is increased by carbon dioxide.

For sensory irritation (a toxic effect that depends upon the immediate concentration of an irritant to which the subject is exposed, rather than a dose) – the concept of a fractional irritant concentration (FIC) has been developed, where

$$\mathrm{FIC} = \frac{\text{concentration of irritant to which subject is exposed at time } (t)}{\text{concentration of irritant required to cause impairment of escape efficiency}} \tag{2.2.5}$$

Much of the background material associated with setting tenability criteria for the effects of optically dense irritant smoke is contained in the human behaviour part of this chapter (Section 2.4). A number of attempts have been made to quantify the threshold at which the nature of the smoke (regardless of its asphyxiant, irritant or thermal properties) presents a serious impedance to the ability of occupant to escape. This assessment is based on the degree of visibility afforded by the smoke, although it does attempt to consider the effects of irritation on visibility, such as reduced visual attenuation [14]. The light extinction coefficient (C_s), otherwise referred to as optical density (OD), is the most commonly used measure of smoke obscuration. The relationship between visibility and the light extinction coefficient is complex, and depends on a number of parameters, such as the reflectance and/or contrast of the object being viewed. More information on this subject is contained in Jin's chapter of the SFPE Handbook [14].

Most studies recognise that occupant familiarity with the means of escape does play a part in determining the tenability threshold as well, i.e. the more familiar the occupant with the escape route, the greater the degree of visual obscuration required to impede escape. Jin [14] suggests a tenability limit of extinction coefficient 0.15/m (OD/m = 0.06) for subjects familiar with an escape route, or 0.5/m (OD/m = 0.2) for subjects unfamiliar with the escape route. Purser cites a paper by Rasbash in *Fire International* that suggests a 10 m visibility limit (equivalent to OD/m = 0.08), and another publication by Babrauskas (*Technical Note 1103*, National Bureau of Standards, 1979), suggesting a tenability limit of extinction coefficient 1.2/m (OD/m=0.5) in the context of domestic fires.

Purser states that in order to assess the visual obscuration of smoke, a concept of fractional effective concentration (FEC) has been developed, whereby the smoke concentration is expressed as a fraction of the smoke concentration considered to significantly affect escape efficiency. If the total FEC_{smoke} reached unity, then it is predicted that the level of visual obscuration would be sufficient to seriously affect escape attempts.

Purser provides the following equations for calculating FEC_{smoke}.

$$FEC_{smoke} = [OD/m]/0.2 \text{ for small enclosures} \quad (2.2.6)$$

$$FEC_{smoke} = [OD/m]/0.08 \text{ for large enclosures} \quad (2.2.7)$$

2.3. Television Fires

It is apparent from inspecting a modern television set that the plastic casing makes up the majority of the fuel load. The internal componentry does contain combustible material, but its contribution is minimal by mass. The majority of the television's mass is concentrated in the cathode ray tube, which is made of glass, and is incombustible. Observations made at the New Zealand Fire Service live fire demonstrations in Long Bay, Auckland also indicate that the plastic casing provided the majority of the combustible material in the set. The following section contains a summary by author of some of the more prominent studies carried out on television set fires.

2.3.1. Harwood

Plastic is the cabinet material of choice in televisions, and has been since at least 1972, according to production data supplied by manufacturers [15]. By 1976 around 56 percent of colour television sets sold in the United States were reported to have been made primarily with plastic cabinet material, and half of the remaining sets included a combination of plastic with some other material. This allowed for an interesting comparison with television sets that still had wooden or metal casings. According to Harwood [15] a consistent hierarchy was observed in TV fires: plastic cabinets were at highest fire risk, metal or wood at lowest risk, and combination models somewhere in between. If it is assumed that similar internal componentry was used, then this indicates that the casing material plays the most important role in the development of television set fires. Harwood points out that the absolute risk of television set fires appears to be low. The highest fire rate observed in 1970 colour models in the US was 54 per million over a two-year period, or about 27 fires per million sets per year.

2.3.2. Troitzsch

A study carried out by Troitzsch [16] at the State Materials Testing Establishment MFPA in Leipzig, Germany, on the ignition and post-ignition behaviour of TV sets has shown that housings and backplates made of plastics only meeting low fire safety levels will dramatically contribute to the development of a fire. Troitzsch conducted a comprehensive fire testing programme, including tests in a fully furnished room. His study found that TV sets used in the USA and Japan complying with the UL 94 V [17] fire safety levels did not lead to fire propagation, whereas television sets of European origin with low UL 94 HB fire safety levels readily ignited when exposed to the lowest intensity ignition source. It should be noted that television sets for the New Zealand market are required to comply with AS/NZS 60065:2003 [18] which requires the TV casing to meet the HB classification.

In the UL 94 horizontal burning (HB) test, the flame travelling between two marks on a horizontal test specimen may not burn faster than 38 mm/min for specimens having a thickness of between 3-13 mm. A V-0 classification means that a vertical test specimen may not sustain combustion after being contacted with the flame of a gas burner. V-1 and V-2 tests are less stringent and allow for extended afterflame or afterglow times, and in the case of V-2, some flaming droplets.

In his paper Troitzsch referenced the Fire Statistics United Kingdom 1993, published by the Home Office. This indicated that in 1993 electrical appliances caused 5,764 fires in the UK, which is around 14 percent of all household fires. 441 of these fires were caused by television sets. Troitzsch also reports that the Swedish Electrical Equipment Control Office SEMKO indicated that 150 to 250 television fires take place every year in Sweden.

Troitzsch studied old and new TV sets from Europe, USA and Japan. Part of this study involved an elemental analysis of the backplate plastics to identify the plastics themselves and the nature of the flame retardant systems used. The results showed that all TV set backplates consisted of polystyrene (mostly high impact grades). The flame retardancy of the plastic casings was established using the UL 94 classification.

The tests revealed that TV backplates made of flame retarded plastics usually met the high requirements of the vertical flame spread tests (UL 94 V), while the non-flame retarded plastics only met the lower horizontal test (UL 94 HB) requirements.

Tests with an external ignition source of growing intensity showed that flame retarded UL 94 V plastics generally do not burn, whereas non-flame retarded HB-rated plastics readily ignite when exposed to the lowest energy source typical of a short-circuit or accidental contact with an open flame. Troitzsch concluded that new TV sets purchased in Germany can in most cases be ignited by the lowest energy ignition source. TV sets bought in Japan and the United States on the other hand have high to very high fire safety levels.

2.3.3. Babrauskas

Babrauskas carried out a study into the hazards presented by both fire retarded (FR) and non-fire retarded (NFR) plastics [19]. The primary goal was to determine whether fire retardancy (achieved by introducing highly effective halogenated flame retardants such as bromine into the plastic matrix [20]) effect a trade-off between decreased burning and increased emission of toxic gas species. It could then be determined whether there was a net safety benefit from the use of fire retardants. The research included a smoke toxicity assessment of polystyrene television casings. Babrauskas found that in small scale tests the peak heat release rate (HRR) of the FR casing was only 35 percent of the value for the NFR specimen (340 kW/m^2 compared to 970 kW/m^2 at an incident flux of 20 kwm^2) and it released only about half as much heat in total as the NFR casing (46 MJ/m^2 compared to 87 MJ/m^2 at a 30 kW/m^2 flux). The effective heat of combustion of the fire retardant casing ranged between 10 MJ/kg and 12 MJ/kg (for 30 kW and 100 kW irradiance respectively), while the NFR casing was approximately 30 MJ/kg. It is interesting to note that the smoke yield per unit mass loss of the FR specimen was about twice that of the NFR one.

Two FR sets and one NFR set were tested as whole units in the furniture calorimeter (using an empty casing sealed at the front with a galvanised steel cover). The FR casings showed a peak HRR of 175-180 kW, whereas the NFR casing peaked at

515 kW. The total heat generated by the two FR cases was 40 MJ, compared to 83 MJ for the NFR case. The average heat of combustion was 20 MJ/kg for the FR cases and 23 MJ/kg for the NFR casing. This differs from small scale tests in this study and others discussed here which have determined the effective heat of combustion of fire retarded high impact polystyrene to be 10-12 MJ/kg and the effective heat of combustion of non-fire retardant high impact polystyrene (HIPS) to be approximately 2.5 times this value. CO production in the FR sets was up compared to the NFR casing, with values of 0.26 kg/kg and 0.48 kg/kg (burned material) compared to 0.12 kg/kg. CO_2 on the other hand was less in the FR casings, at 0.72 kg/kg and 0.72 kg/kg compared to 1.39 kg/kg in the NFR set. The FR casing was not capable of sustained combustion under the ignition criteria used during the testing procedures. Although analysing equipment was in place, HCN and HCl concentrations did not register. In a separate set of tests [21] Babraukas recorded a peak HRR of 570 kW for NFR polystyrene TV casings, and 220 kW for FR polystyrene casings.

Small scale toxicity tests using the N-Gas model and animal exposure experiments found that neither the fire retarded nor un-retarded materials were considered extremely toxic. However the tests did indicate that hydrogen bromide (HBr) may contribute in a small way to the toxic effects produced from burning the fire-retarded casing. Babrauskas concluded that the fire retardant additives did decrease the overall fire hazard in the television sets tested.

2.3.4. Hoffman

A set of ten full scale burn tests of television sets were carried out by Hoffmann et al in the United States [22]. Background information contained in the report estimated that there were 940 fires a year in the US attributable to television sets. This is out of an average of 364,540 residential fires, making TV sets responsible for 0.25 percent of these fires. The report goes on to estimate that as of 2003 there were 2.4 fires per million TV sets per year in the United States. In comparison, the study cites 1979 statistics that show there were 34.4 fires per million colour TV sets with HB rated cabinets, and only 4.6 fires per million colour TV sets with V-0 rated casings. The study concluded that television sets made of V-0 rated plastics (for the US market) will not ignite and propagate a flame under the test conditions whereas TV sets manufactured using HB rated plastics (for the European market) will ignite and propagate a flame under the same test conditions. An analysis of the composition of the plastic casing of a V-0 rated television determined that it was polystyrene based with flame retardants which contained bromine and antimony. Analysis of the European TV set revealed that the casing was primarily polystyrene. Cone calorimetry tests of the V-0 casing gave a peak HRR of 224 kW/m^2, and an effective heat of combustion of 11 MJ/kg, at an incident flux of 20 kW/m^2 and 10 MJ/kg at an incident flux of 40 kW/m^2. This is consistent with the findings in the Babrauskas study discussed earlier. Oxygen consumption calorimetry during a room scale test revealed that the HB rated European television set had a peak HRR of 455 kW, and the V-0 constructed US television sets had an average peak HRR of 302 kW (including the ignition source). It should be noted that the peak HRR of the V-0 rated set included the ignition source, as self-sustained combustion was not achievable.

2.3.5. De Poortere

A study by De Poortere et al [20] raised concerns about the increasing number of TV fires in countries such as the UK, Sweden and the Netherlands. The study linked this trend to the international standard IEC 65 [23], which requires that TV enclosure materials only meet the UL 94 HB classification. De Poortere then made comparisons with fire statistics in the US. The study estimated that the number of TV fires in Europe was 100 per million TV sets per year due to internal ignition sources, at least an order of magnitude higher than in the United States. This may be explained by the fact that US regulations require televisions to comply with UL 1410 [20], which specifies V-0 materials for TV enclosures. The relaxation of fire retardancy requirements in Europe has resulted from legislative changes aimed at restricting the use of certain halogenated flame retardants. The study noted numerous other research however showing that brominated flame retardants can be safely used by society to provide necessary protection from fires. Other points of note from this research include an estimate that a modern TV can contribute approximately 165 MJ to a fire. This is equivalent to 5 litres of petrol. The second point of interest is the finding that in Germany, 30-40 percent of fires did not spread beyond the television set. Finally, the report also noted that approximately one third of television fires originated from an external ignition source, and identified candles as being a particularly common cause.

2.3.6. Blomqvist

A further study on TV set fires by Blomqvist et al [25] concentrated on organic species such polycyclic aromatic hydrocarbons (PAH) and polychlorinated dibenzodioxins/furans, more commonly referred to as dioxins. The emission of organic species is not of major concern for people during a fire (but may be a post-fire hazard), however the research did include some observations pertinent to this study. Detailed chemical analysis was conducted on the high impact polystyrene enclosure of both a European HB rated set, and a US V-0 rated set. The enclosure material of the US TV contained decabromodiphenylether (deca-BDE) and antimony oxide (Sb_2O_3) as flame retardant whereas the enclosure material of the European TV contained no flame retardant additives. In full-scale tests the NFR European TV set was ignited by a match sized ignition source and burnt with a maximum HRR of approximately 240 kW until essentially no combustion material remained. The US TV set with FR enclosure material did not sustain combustion once the ignition source was removed. An external ignition source of 30 kW in contact with the TV for the duration of the test was needed in order to achieve combustion. The maximum HRR in this experiment was approximately 100 kW excluding heat released from the burner. The results for the full scale tests revealed CO yields of 0.068 g/g and 0.104 g/g (burned material) for the European and US sets respectively. With regard to CO_2 the yields were 3.28 g/g and 1.48 g/g respectively, while hydrogen chloride (HCl) yields were approximately 0.006 g/g and 0.015 g/g. The study concluded that the presence of a flame retardant additive had a marked effect on the combustion products. The yields of all the products of incomplete combustion measured, including CO, volatile organic compounds (VOC) and PAH, were significantly higher for the TV set with a fire retarded enclosure. It must be emphasised however that the comparison is tenuous given the difference in fire scenarios created by the need for continuous use of the 30 kW burner during the FR casing test. It was noted that this would not normally represent a typical residential fire scenario involving a television set, although it could be argued that the burner might represent another more combustible appliance located in close proximity to the TV set.

2.3.7. Fire Research Station

An extensive UK study [26] on television fires was commissioned by the Consumer Affairs Directorate, and carried out at the Fire Research Station (FRS). This study found that of an average 55,000 fire incidents in UK homes over the fire years 1994 – 1998, electrical sources accounted for 58 percent of the incidents. Television sets accounted for 2 percent of overall fire incidents in homes from electrical sources, which was the lowest of the key electrical sources analysed. On average over this period there were about 16.4 fires per million TV sets in the UK. The study also found that TVs account for 4 percent of all fatalities caused by fires from an electrical source. A fatality occurs in 4.8 out of every 1000 TV related fire incidents attended by brigades. This represents an average of 0.09 deaths per million TVs each year over the five year period. The ratio of fatalities in TV incidents in the UK is significantly lower than for other electrical sources such as electric blankets and space heaters, though this may be due to increased intimacy of the victim with the source in these cases, particularly with respect to electric blanket fires. The study also identified the risk of a non-fatal injury from a TV fire as averaging 4.7 per million sets over the five year period. It was not possible however to determine the seriousness of these injuries, and given the increasing trend in the UK to refer anyone involved in a fire for a medical check up whether obviously injured or not, the data could be significantly overstating the risk of serious injury.

The report went on to say that the available data indicates around 20 percent of TV fire incidents are caused by external sources and suggested that the proportion may be higher still (possibly up to 40 percent). The research concluded that while HB rated TV enclosures (as required by the European standard IEC 65) appear to give an adequate level of protection from the risk of fire started by an internal fire source, TV sets manufactured to this standard could be easily ignited by a low energy external ignition source such as a nightlight (tea light candle). It should be noted that this conclusion is at odds with other studies discussed in this section which found HB rated enclosures could be ignited from an internal ignition source such as a low power short circuit. The study found that once ignited, all TV sets (HB and V-0) burn fiercely and give off toxic smoke. Also of interest was the finding that there was a 60 percent probably that the fire would spread from the television set to ignite other objects. This is a very similar percentage to that found in the De Poortere study [20].

Calorimeter tests involving televisions purchased in both the UK and US were carried out at the FRS as part of this study. While the two UK sets could be ignited with a nightlight (double wicked with two matches), the two similar American sets could not be ignited in this manner. A third US set was tested using a 30 kW burner to sustain combustion. The tests found that this American set had a peak HRR of 177 kW, compared to the 230 - 248 kW for the British sets. Smoke production was less overall in the American set, 4234 m^3, compared to 4494 m^3 and 4566 m^3 in the British sets, but peaked at a higher rate. This is in contrast to the Babrauskas study [8], which found smoke yields to be approximately double in the FR American sets compared to the NFR European sets. Peak CO production for the UK sets was recorded as 0.036 - 0.038 percent, as opposed to 0.086 percent for the US set. Peak CO_2 production for the UK sets was 0.545 percent and 0.526 percent, whereas for the American sets it was only 0.277 percent. As with the other studies discussed previously, the different ignition methods used during the tests need to be considered when assessing these results. Nevertheless, one of the conclusions of the calorimetry tests was that the presence of fire retardant in the US sets was very effective in reducing ignition and promoting self-extinction.

2.3.8. TUKES

A study by TUKES [27] found that fires originating from a television set make up approximately 12 percent of all electrical fires in Finland. This translates into some 200 fires annually. Expressed as a proportion of television sets in Finnish homes, the incidence of TV fires is approximately one out of every 17,000. As a comparison, the frequency of electrical fires caused by cookers, sauna stoves or central vacuum cleaners in Finland is on average double the frequency of that for television sets.

According to fire experiments conducted at the VTT Technical Research Centre of Finland, TV fires produce a fairly high amount of thermal power, in the order of 250 - 300 kW [26]. This study goes on to say that of all home appliances, only refrigeration equipment and dishwashers burn with a greater intensity. The research also found that smoke release in TV fires is three times greater than in fires involving refrigeration equipment. According to this Finnish study, having once ignited the fire progressed rapidly. The elapsed time from ignition to full strength was only 1 - 2 minutes. This was at odds with observations made during the Fire Service live fire demonstrations conducted at Long Bay, Auckland, in February 2003. This may indicate differences in the materials used in the TV casings, or possibly different ignition methods.

The Finnish study recorded temperatures of 200 - 250°C when television sets were burning alone in a small room. In larger sitting rooms the temperature remained at 100 - 150°C. It was not clear from the literature where within the room these temperature readings were taken. The study concluded by stating that experiments with TV sets in which fire retardants were used have shown that such sets did not achieve self-sustained flaming combustion. Once external flame employed in the experiment was removed, smoke release ceased of its own accord. European standards require that fire retardant materials be used in parts of TV sets that are particularly sensitive to fire. The casing however, is not considered such a part. According to the study, a TV set casing that meets European minimum standards may easily be ignited by a low-power short circuit or open flame.

2.3.9. Comparison of Findings

The following graphs summarise the heat release rate findings of the studies covered in this section, along with the statistical data on the occurrence of TV fires. Not surprisingly, the graphs reveal that not only is the fire size likely to be more substantial with an unretarded television casing, but the chance of fire occurring is also significantly increased.

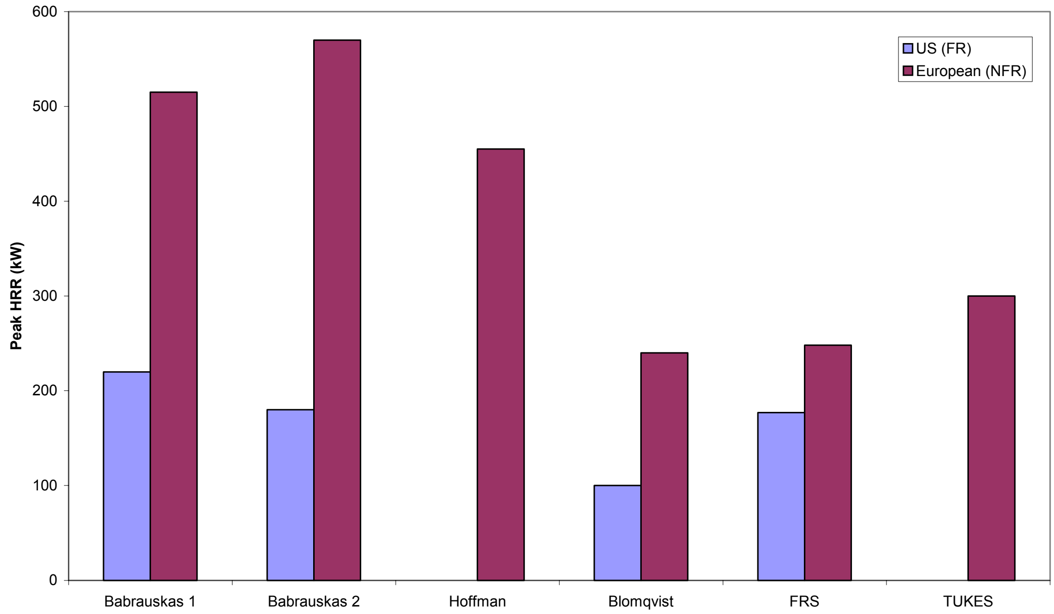


Figure 2.3.1: Comparison of peak HRR values

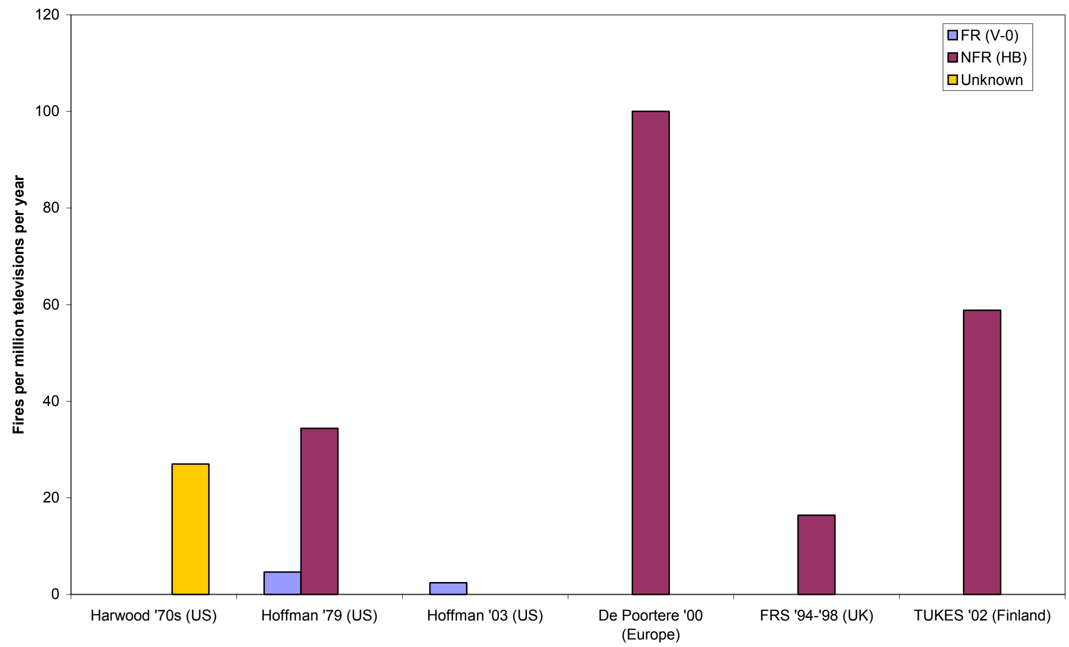


Figure 2.3.2: Comparison of fire incidents in FR and NFR TV sets

2.4. Human Behaviour in Smoke

Human behaviour in smoke is particularly relevant to this study because it determines in large part the time required for an occupant to escape from the apartment. The decision making processes of the occupant may be affected by psychological factors such as fear or panic, or physiological factors such as sensory and respiratory distress. The reduction in visibility caused by smoke will also affect the movement speed of the occupant.

Keating [28] interviewed 100 participants of single dwelling residential fires and reported no instances of panic behaviour and instead found primarily altruistic, helpful behavioural responses. According to Bryan [29], the principal variables influencing an occupant's decision to move through smoke appear to be recollection of the location of the exit, and ability to estimate the travel distance required. Secondary variables are the perception of the severity of the smoke (determined by observation of the appearance of the smoke), the smoke density, and the presence or absence of heat with smoke. Bryan noted that occupant behaviour varies extensively in the presence of smoke. Some occupants have been known to move through smoke for extended distances (over 20 m) under conditions of extremely limited visibility (less than 4 m), at personal risk in order to achieve evacuation. On other occasions occupants have been forced to turn back by smoke and not complete the evacuation.

In a study of participants in fires in the US [30], Bryan found that 107 of the 584 participants did not leave the fire incident building voluntarily. Of these, over 11 percent could not because they were either blocked by smoke or overcome by smoke. A further 5.6 percent were either blocked by fire or afraid of fire spread. However 322 persons who did evacuate reported that they moved through smoke in the process. Information from Bryan's study is compared to data collected in a British study of by Wood [31]. 60 percent of the population of the British study (1316 persons), and 62.7 percent of the US study reported that they moved through smoke. Occupants reported their movement through smoke in relatively high smoke-density conditions, with visibility below 4 m (C_s = 0.5 1/m) for 64 percent of the British population and for 47.6 percent of the United States population. Bryan and Wood also looked at the visibility distance at the time the participants were forced to turn back. The results indicated that very few participants turned back while the visibility exceeded 10 m (C_s = 0.2 1/m). 91 percent of the British population who turned back, and 74.6 percent of the US population, initiated their behaviour at visibility distances of less than 4 m. The information from both these studies was derived in most part from residential property fires housing occupants familiar with the means of egress. It should also be noted that the data on visibility is a subjective assessment on the part of the occupant interviewed, based on observations of normal objects and backlit exit signs made during the evacuation.

In Proulx's chapter in the SFPE Handbook on the movement of people [32], she notes that the movement of people through smoke is a reoccurring event in actual fires. She goes on to say that although it seems well known by the public that it is smoke that kills people in fires, occupants are still prepared to move through smoke to reach safety. The public knowledge that smoke kills does not mean that they are a good judge of the potential lethal effect of smoke. Victims are reporting that they made it through smoke because they moved very fast, or were breathing through a cloth or holding their breath to protect themselves. Proulx suggests that a motivation for moving through smoke in high-rise buildings is the strong desire of occupants to reach ground level.

Proulx refers to a series of tests in Norway by Jensen involving 80 subjects, which found that under smoke optical density of 1.09 and 1.58 1/m, movement speed was around 0.2 to 0.4 ms^{-1}. This is considered to be the limiting speed of movement in smoke, regardless of what egress information is available to the occupant. Those who have survived catastrophic fires moved on average only 10 m in heavy smoke. At a speed of 0.2 ms^{-1}, this equates to an exposure time of 50 seconds. In another paper [33] Proulx studied occupant response to a fire in a high-rise apartment building. Of 114 occupants who attempted to escape, 84 percent reported moving through smoke. 45 percent of those moving through smoke indicated that they could see "nothing at all" or "little" while 30 percent said they could see 12-15 m down the corridor. 54 percent of those who attempted to escape were successful, while the remaining 46 percent were turned back by smoke conditions in the corridors and stairs.

Following a series of experiments involving human participants, Jin [14] noted that visibility in fire smoke depends on its irritating nature as well as the optical density of the smoke. When highly irritating smoke from smouldering wood cribs was used, the experiments revealed a sharp drop in the walking speed of the subjects as the density of irritant smoke increased, with speeds of around 0.3 ms^{-1} estimated in smoke where the extinction coefficient (C_s) exceeded 0.5 1/m. In tests using non-irritating smoke produced by burning kerosene, subjects walking speed reduced to 0.5 ms^{-1} when the extinction coefficient reached 1.0 1/m. Normal walking speed in good visibility is approximately 1.2 ms^{-1}. In the case of the irritant smoke participants could not keep their teary eyes open, indicating that visual acuity plays a part along with optical density in determining visibility.

Jin also evaluated both the psychological and physiological responses of test subjects to increasing smoke density in a small room. He concluded that people unfamiliar with the room experienced unease at an extinction coefficient of 0.15 1/m. Most subjects reported that the drop in visibility was the dominant factor causing their unease. People familiar with the environment tended not to experience significant adverse emotional responses until the smoke density reached 0.35-0.55 1/m. In this case it was the physiological effects of irritation and suffocation that gave rise to the unease, rather than the reduction in visibility. Jin concluded that people who know the inside geometry of a building on fire need a visibility of 4 metres (C_s = 0.5 1/m) for safe escape while those who do not need a visibility of 13 metres (C_s = 0.15 1/m). In the case of an apartment fire, it is reasonable to expect the occupant to be familiar with the environment, so the first case is of more interest.

In the SFPE Handbook, Jin [14] refers to another study he did involving a group of subjects (14 males and 17 females) travelling individually down a 10.5 m corridor exposed to smoke from smouldering wood chips. During the tests the smoke extinction coefficient C_s was equal to 0.92 ± 0.21 1/m. The subjects were exposed to increasing heat from radiant heaters at the end of the corridor, giving an average air temperature of 82°C and a maximum heat flux of 2.4 kW/m^2 at a height of 1.5 m at the end of the corridor. At five points along the corridor the subjects were required to perform mental arithmetic calculations. The results of the tests showed that both walking speeds and mental arithmetic capability decreased with the increase in smoke density and increase in radiant heat exposure. In tests where the smoke density was greatest (i.e. $C_s = 1.13$ 1/m), 14 of the 31 subjects turned back before reaching the end of the corridor. Of these 14, 8 were male and 6 female. It is not apparent from the literature whether the subjects were familiar with the corridor prior to the tests, or whether they had knowledge of the length of the corridor before they entered it.

3. Fire Safety Systems

3.1. Smoke and Fire Detection inside the Compartment

In order to evaluate the implications of removing smoke detection and relying instead on fast response residential sprinklers to enable occupants to safely evacuate the apartment in the event of fire, it is first necessary to gauge the level of protection that smoke detection actually affords. This is also an opportunity to assess the performance of alternative forms of fire detection. In this analysis four different types of detectors were evaluated:

- Ionisation
- Optical (Photoelectric)
- Carbon Monoxide
- Thermal

Ionisation and photoelectric smoke detectors comprise the majority of smoke detectors currently in use. Ionisation detectors respond better to faster developing, clean burning fires, whereas optical detectors tend to perform better in smouldering fires [34]. Of the two, ionisation detectors are more prevalent in New Zealand at present.

Carbon monoxide detectors are a relatively new technology, and as the name suggests, detect the presence of CO rather than smoke particulates. It is therefore possible that CO detectors are less sensitive to the cooking fumes that generate so many unwanted alarms with more traditional smoke detection systems. CO detection has been included in the experiments to evaluate its performance against the standard methods of smoke detection.

A thermal detector responds to heat from the fire, rather than smoke particulates and is therefore unaffected by cooking fumes. Although both thermal detectors and sprinkler heads are activated by heat, a thermal detector will normally have a lower response time index (RTI) than a sprinkler head, and should therefore respond to heat from the fire more rapidly than the sprinkler. So while it is not expected that a thermal detector will be as responsive as smoke or CO detectors, it has been included in the experiments to determine if its lower RTI gives it a significant advantage over the sprinkler system in terms of early warning.

3.2. Smoke Detection in Adjacent Space

In its basic form, the proposal to remove the smoke detection relates only to the living area of the apartment. It has been assumed that distance, along with the natural barrier formed by the door lintels, will prevent cooking fumes from causing unwanted activations by smoke detectors situated in adjacent spaces.

In small apartments, the only adjacent spaces of any consequence are likely to be the bedrooms, which generally open directly off the living space. It is therefore reasonable to assume that in the event of a fire in an apartment where smoke detection has been removed from the living area, the first warning occupants receive will be from a smoke detector activating in a bedroom.

To evaluate this possibility, the performance of smoke detectors in a space directly adjacent to the fire compartment was examined during some of the experiments. In every case the connecting door between the two spaces was closed. Two types of smoke detectors were used in the adjacent space:

- Ionisation
- Optical (Photoelectric)

These two detectors are identical to the ones of the same type mounted inside the compartment. The object of the exercise was to monitor their response to smoke entering the adjacent space through the gap around the closed door connecting the two spaces (see Figure 5.2.1 and Figure 5.2.2). The activation time of the smoke detectors in the adjacent space can then be compared to that of the detectors in the compartment, as well as the activation time of the sprinkler system.

3.3. Sprinkler System

The basis of the proposal to remove smoke detection from the living area of the apartment is reliant on the reaction time of the fast response residential sprinkler head. The operating mechanism of the fast response residential sprinkler head is similar to the majority of modern conventional heads. The thermally responsive liquid inside a frangible glass bulb is heated through a process of convention from the hot fire gases following past the head, and to a lesser extent by radiation from the fire itself. As the liquid is heated, it expands until a point is reached where the glass bulb shatters, allowing water to flow out of the sprinkler head. Residential sprinkler heads are designed to discharge water in a wide spray pattern to ensure coverage of the walls of the room, against which the majority of furniture is usually located, along with curtains and other potentially flammable wall hangings.

A fast response residential sprinkler head differs from a conventional sprinkler head because the frangible bulb is significantly smaller. Where the bulb in a conventional sprinkler head is normally around 5 mm in diameter, the bulb in a fast response residential sprinkler head is 3 mm in diameter or less. This means that there is less thermal mass within the bulb, and a greater surface area to mass ratio. Therefore for gas at a given temperature flowing past the sprinkler head at a given velocity, the liquid inside the bulb of the fast response residential sprinkler head will heat up more rapidly than the liquid inside the bulb of a conventional sprinkler head. In other words, under the same fire conditions, a fast response residential sprinkler head will activate sooner than a conventional sprinkler head.

The responsiveness of a sprinkler head is denoted by its response time index (RTI). The smaller the RTI, the fast the sprinkler head responds. The RTI of a fast response residential sprinkler head is between 28 $m^{½}s^{½}$ and 50 $m^{½}s^{½}$, while the RTI of a conventional sprinkler is approximately 100 $m^{½}s^{½}$ to 350 $m^{½}s^{½}$ [35]. One of the primary goals of this research was to determine if the reduced RTI of the fast response residential sprinkler head allowed it to operate soon enough to provide a sufficient level of safety to the occupant/s of the apartment.

A second objective of the research was to determine what effect sprinkler activation had on tenability within the compartment. If sprinkler activation was to fulfil the role of both warning device and fire control, then the act of suppressing the fire must not jeopardise the occupants escape attempt. The convection driven buoyancy of smoke in the fire plume means that it would naturally tend to form a layer at ceiling level, which would descend in a fairly uniform manner as the fire progressed. This would leave a relatively clear layer of air beneath the smoke, affording occupants an opportunity to escape safely. Activation of the sprinkler system would cool the upper smoke layer, causing it to descend into the previously clear layer beneath (commonly known as downdrag). This would not only affect visibility, but would also bring any toxic combustion products such as carbon monoxide down into the lower level of the room. If occupants attempted to evacuate through the living space after sprinkler activation, this could affect their ability to safely escape.

It should be recognised that sprinkler activation will at least suppress fire development, if not extinguish it completely. This in turn should reduce the amount of toxic combustion products being given off by the fire, making the environment less hazardous. However it is possible for partial suppression to lead to inefficient combustion which could increase the production of carbon monoxide. This scenario is particularly relevant in the event of the fire being shielded from the sprinkler spray by an item of furniture or fixture within the room for example. Another factor that should be considered when evaluating the implications of sprinkler activation is the possibility that the water spray will dilute or wash out toxic combustion products. This is certainly a distinct possibility with regard to solid particulates, which can be absorbed by the spray droplets and removed from the atmosphere within the room. For these reasons an attempt was made to analyse the tenability conditions within the compartment following sprinkler activation, as well as prior to activation.

4. Tenability Criteria

4.1. Fractional Effective Dose (Asphyxiant)

As indicated by a variety of sources [3,8,9,12], the combustion products that have the greatest impact on tenability during a fire are carbon monoxide (CO) and hydrogen cyanide (HCN). As there was no method available to take continuous measurements of HCN, the tenability assessment had to focus on carbon monoxide. The presence of HCN is normally associated with the combustion of substances containing organically bound nitrogen [37]. The majority of television casings are likely to be made of high impact polystyrene (HIPS) [16,19,25], and previous studies have not revealed high concentrations of HCN generated by burning polystyrene TV sets [19,20]. It was therefore considered reasonable to ignore the contribution of HCN in the primary tenability analysis. Nevertheless, any assessment of the results of this analysis should recognise that the presence of HCN would adversely affect tenability. For this reason grab samples of HCN were taken at discrete intervals during some of the experiments to gauge whether HCN might have had been a factor in this particular fire scenario.

Tenability conditions were determined using Pursor's fractional effective dose (FED) method [3]. Purser gives the following equation for calculating the FED for asphyxiant fire gases:

$$F_{IN} = \left(F_{Ico} + F_{Icn} + FLD_{irr}\right) \times VCO_2 + F_{Io} \qquad (4.1.1)$$

where

F_{IN}	=	fraction of an incapacitating dose of all asphyxiant gases
F_{Ico}	=	fraction of an incapacitating dose of CO
F_{Icn}	=	fraction of an incapacitating dose of HCN
FLD_{irr}	=	fraction of an irritant dose contributing to hypoxia
VCO_2	=	multiplication factor for CO_2-induced hyperventilation
F_{Io}	=	fraction of an incapacitating dose of low-oxygen hypoxia

In order to use Equation 4.1.1 the experiments had to measure the concentrations of carbon dioxide (CO_2) and oxygen (O_2) in the compartment, along with the concentrations of any irritant gases that would contribute to hypoxia by affecting airway and lung function.

As already stated, HCN concentrations were not going to form part of the analysis. With regard to irritant gases, it appeared that hydrogen chloride (HCl) would be the most common [3,25]. However HCl is generally evolved during the combustion of polyvinyl chlorides [37] and is not likely to result in significant quantities from the combustion of high impact polystyrene [19,20]. Therefore the concentration of irritant gases was not included in the FED analysis. Nevertheless, as with HCN the presence of HCl was gauged by taking grab samples at discrete intervals during some of the experiments.

This resulted in the use of a simplified FED calculation which looked at the concentration of CO, and took into account CO_2 induced hyperventilation and the effects of low oxygen hypoxia. The modified equation is as follows:

$$F_{IN} = F_{Ico} \times VCO_2 + F_{Io} \tag{4.1.2}$$

The methods for calculating the individual FED components are as follows:

$$F_{Ico} = \frac{K\left(ppm\,CO^{1.036}\right)(t)}{D} \tag{4.1.3}$$

where

K	=	8.2925×10^{-4} for 25 l/min RMV (light activity)
t	=	exposure time (min)
D	=	COHb concentration at incapacitation (30 percent for light activity)

$$VCO_2 = \frac{\exp\left(0.1903 \times \%CO_2 + 2.0004\right)}{7.1} \tag{4.1.4}$$

$$F_{Io} = \frac{(20.9 - \%O_2)(t)}{(20.9 - \%O_2)(t_{Io})} \tag{4.1.5}$$

where

t_{Io} = time to incapacitation due to oxygen depletion

$$t_{Io} = \exp[8.13 - 0.54(20.9 - \%O_2)] \tag{4.1.6}$$

When calculating the fraction of an incapacitating dose of CO, a light activity rate has been assumed. The expectation is that the occupant/s will have been alerted to the fire and will be attempting to escape from the apartment. However under these circumstances it is likely that the occupant/s will be in a highly agitated state, with a corresponding increase in cardiovascular activity. Therefore it should be noted that actual values may exceed the respiratory minute volume (RMV) and carboxyhemoglobin (COHb) concentration for light activity.

Incapacitation as a result of asphyxiant gases is predicted to occur when F_{IN} in Equation 4.1.2 reaches unity. However in order to allow for differences in sensitivity and to protect susceptible human subpopulations, Purser recommends that a factor of 0.1 FED be used to allow for safe escape of nearly all exposed individuals. It should be noted that this is a qualitative assessment and that different values are recommended in other literature, such as 0.3 as suggested in ISO/TS 13571 [7]. For the analysis contained in this report, Pursor's tenability threshold for FED (asphyxiants) of 0.1 has been used as it represents a more conservative value.

4.2. Fractional Effective Concentration (Smoke)

One of the major factors that will affect the ability of an occupant to escape successfully from the apartment will be the degree of visual obscuration caused by the smoke. It can be argued that because the occupant is familiar with the apartment layout, and the distances are not great, smoke obscuration would not absolutely prevent them from making an escape.

It is difficult to say with any certainty however how individuals would react when unexpectedly confronted by heavy smoke, even in their own home - or perhaps particularly in their own home. At the very least smoke obscuration would increase the amount of time it would take an occupant to navigate through the apartment, which in turn would increase the dose of asphyxiant gases they were exposed to.

It is important to also realise that loss of visibility due to smoke is not the same as simply being unable to see. In the case of smoke, loss of visibility is usually accompanied by irritation of the eyes and respiratory system, seriously affecting an occupant's ability to tolerate the environment. If the occupant is unable to escape the environment within a certain time, they may be forced to abandon the attempt. This is regardless of any effects caused by exposure to heat or asphyxiant gases.

The effects of visual obscuration are difficult to quantify due to the subjectiveness of any test method. Nevertheless a value of 1.0 using Purser's FEC_{smoke} equation has been used to determine the threshold at which the level of visual obscuration will seriously affect escape attempts (see Equation 4.2.2). For the purposes of this analysis the FEC_{smoke} threshold is used to in conjunction with the occupant alert time provided by the various fire safety systems. This information will aid in determining whether the available escape time prior to exceeding the FED threshold is adequate.

While exposure to the asphyxiant gases is assessed as a dose, i.e. both the concentration of gases and the duration of exposure are taken into account, the tenability threshold for visual obscuration from smoke is a function of the concentration alone.

The tenability limit is considered to have been exceeded immediately upon the concentration reaching a certain level, regardless of the duration of exposure. In the case of smoke obscuration, Purser [3] defines the tenability limit as time-to-escape efficiency impairment, or loss of tolerability.

Visual obscuration is frequently expressed in terms of optical density per metre (OD/m). Schifiliti et al [36] use the following equation to define optical density per metre:

$$D_u = \frac{1}{l}\log_{10}\left(\frac{I_o}{I}\right) \tag{4.2.1}$$

where

D_u	=	optical density per metre
l	=	light path length (m)
I_o	=	intensity of the incident light
I	=	intensity of the light through smoke

Purser provides a method for calculating the fractional effective concentration for smoke in small enclosures by using the following equation:

$$FEC_{smoke} = [OD/m]/\,0.2 \tag{4.2.2}$$

Purser states that if the total FEC_{smoke} reaches unity, then it is predicted that the level of visual obscuration would be sufficient to seriously affect escape attempts. Unlike FED (asphyxiants), no safety factor has been applied to this value during analysis of these experiments.

4.3. Temperature

As the compartment in which the experiments were conducted was sprinkler protected, the effect of heat on the ability of the occupant/s to escape safely was not considered critical. The assumption being that the fast response residential sprinkler would operate prior to compartment temperatures exceeding safe limits. Nevertheless temperatures within the compartment were recorded as a matter of course, and so an assessment of tenability limits due to heat is possible.

Purser [3] sets the tenability limit for exposure of skin to radiant heat as approximately 2.5 kW/m^2, below which exposure can be tolerated for at least several minutes. For situations where occupants are required to pass under a hot smoke layer in order to escape, Purser states that this heat flux corresponds approximately to a hot layer temperature of 200°C.

While Purser indicates that the tenability limits with regard to skin pain and burns are normally lower than for thermal burns to the respiratory tract, he does state that thermal burns to the respiratory tract may occur upon inhalation of air above only 60°C when saturated with water vapour. This may occur when water is used for fire extinguishment, as in the case of sprinkler activation, however information on the concentration of water vapour in the compartment atmosphere was not recorded during these experiments.

4.4. Heat Release Rate

Although not directly required as part of the tenability analysis, an attempt has been made to determine the heat release rate (HRR) of the fires. The HRR provides useful information on the behaviour of the fire, and may provide some insights into the fire behaviour that most influences tenability in this particular scenario.

Karlsson and Quintiere [38] provide a method for determining the heat release rate for a particular material based on the mass loss rate of the fuel, using the following equation:

$$\dot{Q} = \dot{m}\,\Delta h_c \tag{4.4.1}$$

where

$\dot{Q}$	=	heat release rate (kW)
$\dot{m}$	=	fuel mass loss rate (kg/s)
Δh_c	=	effective heat of combustion (kJ/kg)

The mass loss has been recorded as a function of time from each burning television set, providing a mass loss rate. The majority of the fuel load in a burning TV set comprises the plastic housing. Previous studies [16,19,25] indicate that the most common backing case material for televisions is high impact polystyrene. Babrauskas [19] gives an effective heat of combustion for non-fire retardant polystyrene TV casings of 30 MJ/kg, based on cone calorimetry tests at an incident flux of 30 kW/m^2. This is that value that has been used to determine the heat release rate in these experiments.

5. Experimental Set Up

5.1. Location

The venue for the tests was a large shed with a concrete floor, timber framing and corrugated iron cladding on both the walls and the roof. The shed was approximately 8 metres wide by 18 metres deep. The walls were 3.6 metres high and the apex of the exposed roof truss was at 5.2 metres. A 3 metre wide by 2.8 metre high sliding door was provided in the front face of the shed. The shed was supplied with electricity and a reticulated water supply.

5.2. Compartment Construction

A test compartment to conduct the experiments in was constructed inside the shed. The compartment was modelled on specifications contained in UL 1626 '*Standard for Safety for Residential Sprinklers for Fire-Protection Service*' [39]. The compartment dimensions are those used in the residential sprinkler system performance test for approval under the UL Standard (see Appendix B for floor plan of the UL 1626 compartment). Constructing the compartment to this specification allows for the possibility of work carried out in this analysis to be compared in a meaningful way with any other data obtained using a UL 1626 compartment. It should however be noted that not all the requirements of the UL 1626 compartment were met, such as the number and position of doors.

The compartment was 8 m long by 4 m wide with a stud height of 2.4 m. The floor area of the compartment was 32 m^2, and the volume 77 m^3. This means the compartment is dimensionally comparable to the living and kitchen space found in a typical multi-storey apartment building. If anything its proportions are slightly over generous.

The walls were constructed of 2.4 m high by 1.2 m wide modular 100 x 50 mm timber framed sections, pre-lined with sheets of standard 10 mm gypsum plasterboard. The ceiling was also lined with gypsum plasterboard over 75 x 50 mm strapping on 200 x 50 mm ceiling joists.

A standard 1980 x 810 mm hollow core door set was fitted to one side of the front end of the compartment. Four 910 x 460 mm observation windows of standard 4 mm glass were positioned around the compartment. Two were positioned at floor level and two at a soffit height of 1200 mm. The compartment was raised on blocks 50 mm off the concrete shed floor to allow for water drainage. This 50 mm gap was sealed with removable strips of gypsum plasterboard. All vertical measurements contained in this report ignore this additional 50 mm.

An additional 1200 mm wide sheet of gypsum plasterboard was fixed to each wall abutting the corner where the fires were to be set to give added fire resistance. Joints between gypsum plasterboard sheets on the walls and ceiling were sealed with masking tape. Joints in the wall and ceiling linings in close proximity to the position of the fire were sealed with fire resistant mastic sealant beneath the masking tape. Mastic sealant was also used in the joints surrounding the door to ensure unrealistic smoke migration to the adjacent space was minimised. The walls and ceiling of the compartment were then given a single coat of white acrylic semi-gloss paint to provide a degree of water resistance.

It should be noted that while every effort was made to accurately represent conditions typical of an actual residential apartment, certain differences that might affect fire behaviour within the apartment remained. For example there was no insulation in either the walls or ceiling, nor was there any facing or lining on the outside of the timber framing. This means that heat loss through the compartment boundaries would be greater than that expected in a real apartment.

The ratio of window area to external wall area was also considerably lower than what might normally be found in the living area of an apartment. Windows typically comprise 30 percent of external wall area in a living space. Even with the conservative assumption that only a single end wall of the compartment formed an external wall, the four observation windows represent little more than 17 percent of this area.

The window positions are also unrealistic. A normal window has a soffit height of 2 m. This means that the glass would be exposed to the descending hot gas layer a lot sooner than occurs in the test compartment. This in turn means greater heat loss through the glazing could be expected in a real apartment, and possibly even some cracking of the glass due to heat, altering the ventilation conditions. This final scenario is unlikely to occur however in a fire controlled by fast response sprinklers.

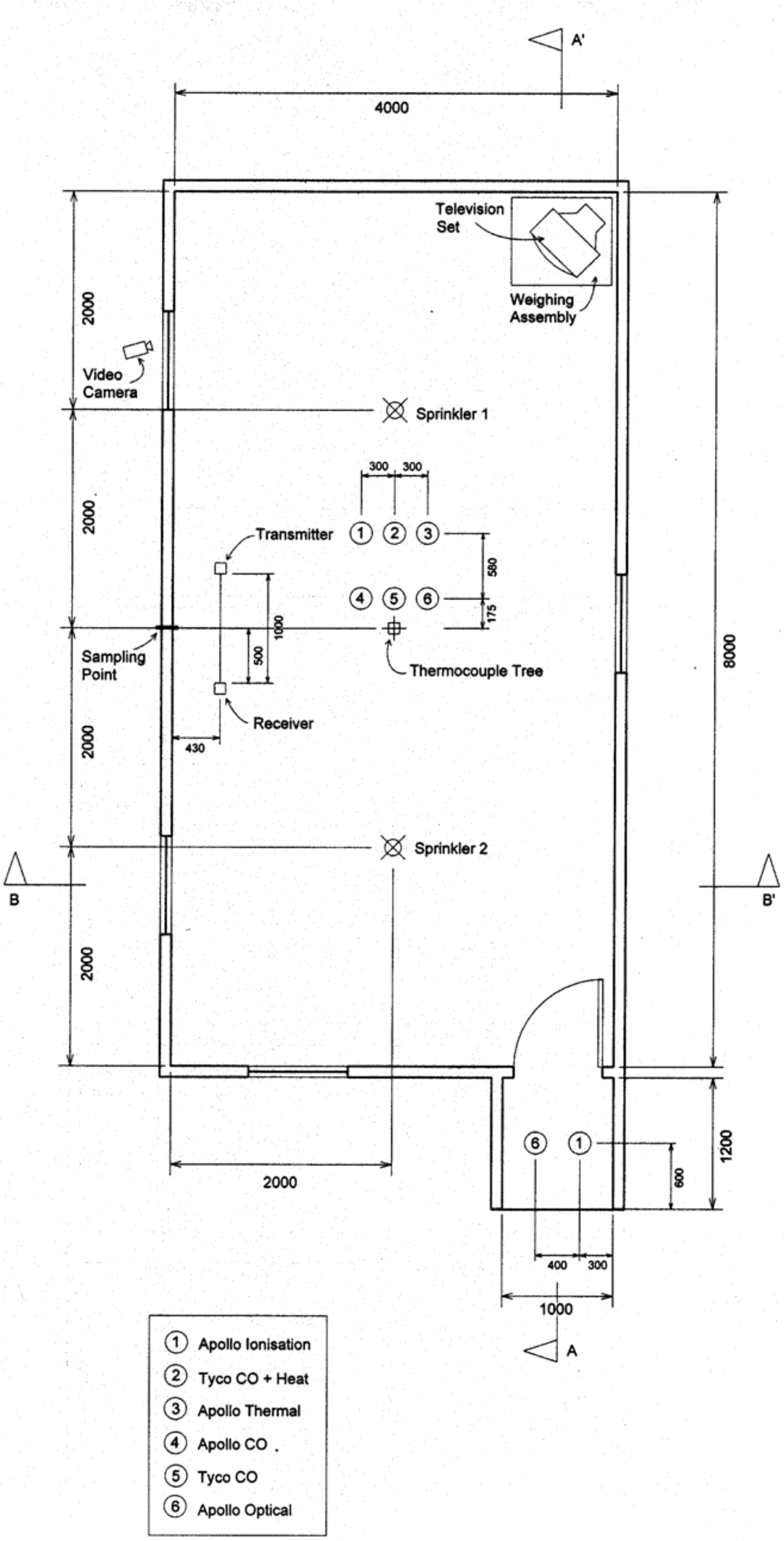
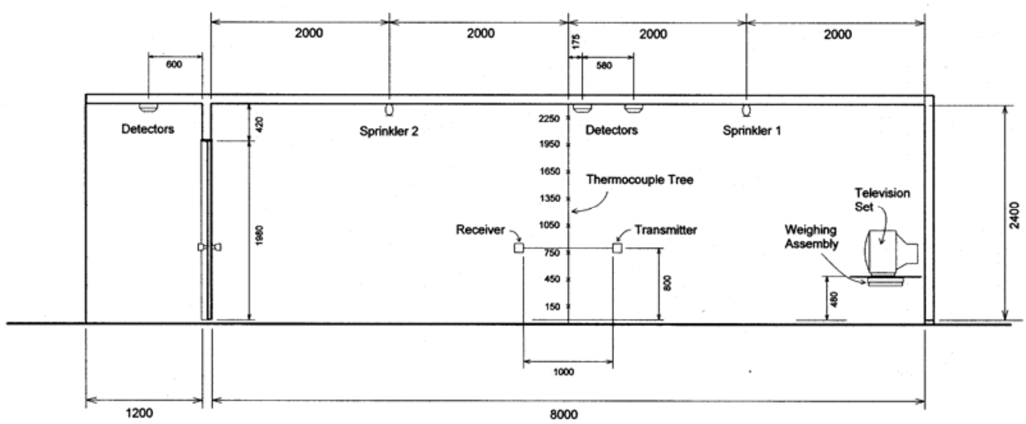
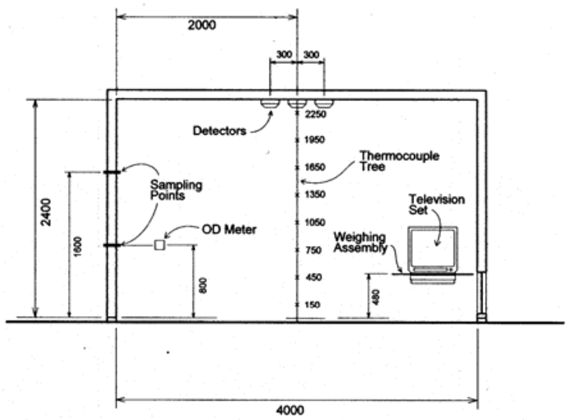


Figure 5.2.1: Test compartment floor plan



Longitudinal Section A – A'



Cross Section B – B'

Figure 5.2.2: Test compartment sectional details

5.3. Adjacent Lobby Construction

During some of the experiments a small lobby was erected around the outside of the door to the compartment. This lobby was intended to represent an adjacent space to the living area within the apartment, most likely a bedroom. The purpose was to measure smoke detector response in a space adjacent to the compartment in which the fire occurred.

The lobby was constructed of two 1.2 m long by 2.4 m high timber framed modular sections lined with gypsum plasterboard sheets. These sections were attached to the outside wall of the compartment, 1.0 m apart, on either side of the door to the compartment (see Figure 5.2.1 and Figure 5.2.2).

A sheet of gypsum plasterboard was fitted across the ends of the sections to form a 1.2 m^2 enclosure outside the door to the compartment. The lower portion of this sheet was removable to provide access to the lobby. Another piece of gypsum plasterboard formed the ceiling to the enclosure. Joints between sheets of gypsum plasterboard were sealed with masking tape. Since no water was expected to enter the lobby, it was left unpainted. The lobby had a volume of approximately 2.9 m^3.

It should be noted that the configuration of the lobby represents a best possible case scenario with respect to the expected activation time of the smoke detectors in this space. For a start the detectors are located within 600 mm of the door to the fire compartment, and the small area of the lobby meant that smoke entering that entered would have little opportunity to dilute. It is therefore reasonable to expect that smoke detection in a real adjacent space, i.e. a bedroom, would not activate any sooner than the detectors in this evaluation, and it is possible that activation could be significantly slower.

It should also be noted that while every effort was made to ensure the compartment and door construction was of the same quality as would be found in a real apartment, constraints inherent in assembling a modular test compartment meant this standard may not have always been achieved. In particular it is likely that the door did not fit to the frame as tightly as might be expected of a standard domestic door set. Therefore more smoke may have passed between the two spaces than would occur in reality, leading to earlier activation of the lobby smoke detectors.

5.4. Smoke and Fire Detectors

The four different types of smoke and fire detectors within the compartment, and the two smoke detectors in the adjacent space, were all mounted on the ceiling, as close as possible to the centre of their respective spaces (see Figure 5.2.1). The location of the detectors complies with the requirements of NZS 4512:2003 '*Fire Detection and Alarm Systems in Buildings*' [34].

The detectors were manufactured by Apollo Fire Detectors (see Appendix C for technical specifications). As they were analogue addressable, their response to the fires could be recorded as a continuous output. The detectors were wired to an interface box connected to a laptop computer. Proprietary software controlled the detectors using communications protocol specified by Apollo and logged the analogue output value from each detector at an interval that ranged between 1 and 2 seconds. The output from this software was in a form that could be imported to a spreadsheet for processing.

An analogue output value of 55 has been set by the manufacturer as the activation threshold for all the detectors. A count of 55 corresponds to the EN54 alarm sensitivity level [40]. With respect to the thermal detector, the analogue count has been calibrated to correspond to the environmental temperature in degrees Celsius, i.e. a count of 55 equates to a temperature of 55°C. The RTI of the thermal detector was approximately 17 $m^{1/2}s^{1/2}$ [41], compared to an expected RTI for a fast response residential sprinkler head of about 36 $m^{1/2}s^{1/2}$ [42].

The supply of detector heads for this evaluation was limited, requiring heads to be reused. Although the detector heads were cleaned at the end of each test, some reduction in performance would inevitably result from repeated exposure to high concentrations of combustion products during successive tests. It should also be noted that compartment gas temperatures at the ceiling often exceeded the detectors maximum temperature. These problems were essentially restricted to the detector heads in the test compartment. The two detectors mounted in the adjacent lobby were subjected to significantly less smoke and heat, and for a shorter duration.

At the end of each test, dust covers were placed over the lobby detector heads to provide some degree of protection prior to opening the door to the test compartment.

Compartment detectors

Lobby detectors (covered)

Figure 5.4.1: Smoke and fire detector locations

It should be noted that a series of detectors manufactured by Tyco Fire and Building Products were also installed in the compartment. Although the Tyco detectors were analogue addressable, no method was available to log their response as a continuous output. This meant that it would be difficult to assess whether a detector had developed a fault due to repeated exposure to the test compartment environment. For this reason these detectors are not included in the analysis.

5.5. Sprinkler System

The sprinkler system installed in the compartment for the experiments used Series LFII residential pendent sprinklers manufactured by Tyco Fire and Building Products (see Appendix C for technical specifications). The sprinkler heads had a nominal operating temperature of 68°C. The heads are tested to the Factory Mutual '*Approval Standard for Automatic Sprinklers for Fire Protection*' [43] which requires the actual activation temperature to be within ± 3.5% of the nominal activation temperature.

The sprinklers were positioned in accordance with NZS 4541:2003 '*Automatic Fire Sprinkler Systems*' [44]. Two heads were located symmetrically in the ceiling of the compartment in line with the longitudinal axis, and 4 metres apart (see Figure 5.2.1). The heads were mounted within standard escutcheon plates, and the centre point of the frangible bulb projected approximately 18 mm below the ceiling. The yoke arms were positioned at right angles to the longitudinal axis of the compartment. The sprinkler heads were plumbed into the domestic water supply of the test facility using 32 mm and 25 mm diameter fusiotherm PPr pipe supplied by Aquatherm NZ Ltd.

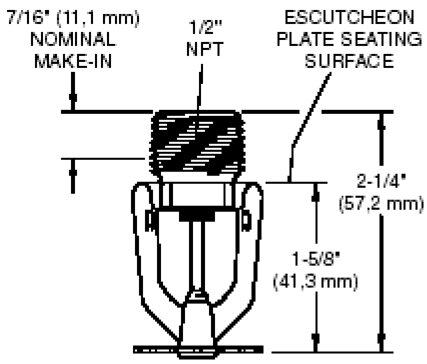


Figure 5.5.1: Tyco Series LFII (TY 2234) Residential Pendent Sprinkler

When tested at the head, a flow rate of 41.5 l/min at a running pressure of 77 kPa was recorded. This test was conducted using a pressure gauge fitted to a Viking M-4 sprinkler head discharging into a graduated collection vessel. The minimum performance requirement for a Viking M-4 head covering 4.3 metres is 49.2 l/min at 63 kPa [45], so the sprinkler system as installed failed to meet the required flow rate by 7.7 l/min. The minimum performance requirement for a Series LFII head at a maximum spacing of 4.3 metres is 49.2 l/min at 48 kPa [46].

Given the similarities between the M-4 head tested and the Series LFII head used in the experiments, it is reasonable to expect that the actual flow rate of the Series LFII head would have been close to that measured from the Viking head. This means that the suppression capability of the sprinkler head would not be a good as that of a system that met the manufacturer's specifications.

While this will not affect any assessment of the tenability conditions prior to, and at, sprinkler activation time, it may have an impact on tenability measurements recorded subsequent to sprinkler activation. During the experiments, sprinkler activation time was recorded on a stopwatch using the distinctive sound of the sprinkler head operating as the indicator. No actual discharge density measurements were made during tests. New sprinkler heads were used for each test, regardless of whether the heads had activated in the previous test or not.

5.6. Gas Analysis

5.6.1. Sampling Methods

During the series of experiments, gas samples were drawn from the test compartment at two different heights, 800 mm above floor level, and 1600 mm above floor level. 800 mm above floor level corresponded to the height at which a person's head might be when attempting to crawl through a smoke logged room. It could also represent the head height of a person asleep in a bed. 1600 mm above floor level represents the approximate head height of a person standing upright. It should be noted that samples were taken from only one height in any given test.

Carbon monoxide and oxygen were both sampled using the same system. Gas was drawn out of the test compartment under negative pressure through a length of ¼ inch flexible PFA tubing and passed through a filter to remove solid particulates, followed by a drying chamber filled with blue indicating silica gel crystals to remove any moisture. Another length of tubing connected the filter/drying chamber assembly to an electric air pump.

From the pump a controlled 3 way valve allowed either the sample gas or calibration gases to be directed to the analysers under positive pressure. Tubing running from the 3 way valve to the analysers was split at an open tee junction taking the sample gas to both the CO analyser and the O_2 analyser (see Figure 5.6.1). The delay time from the sample being drawn from the compartment until registering on the analyser output was 3 seconds. This time lag has been allowed for when processing the analyser outputs.

The carbon dioxide analyser used during these experiments had a built in filter and pump system. A 5 metre length of ¼ inch tubing drew sample gas from the test compartment into a particulate filter and moisture chamber mounted on the rear of the analyser. The delay time from a sample being drawn from the compartment until registering on the analyser output was approximately 9.5 seconds. A 10 second time lag has therefore been allowed for when processing the analyser outputs.

Grab samples of hydrogen cyanide and hydrogen chloride were obtained by inserting the tip of the sampling tube into a hole in the compartment wall and manually drawing the sample into the tube using the sampling pump provided (see Appendix C for technical specifications). The hole in the wall was sealed with masking tape between sampling.

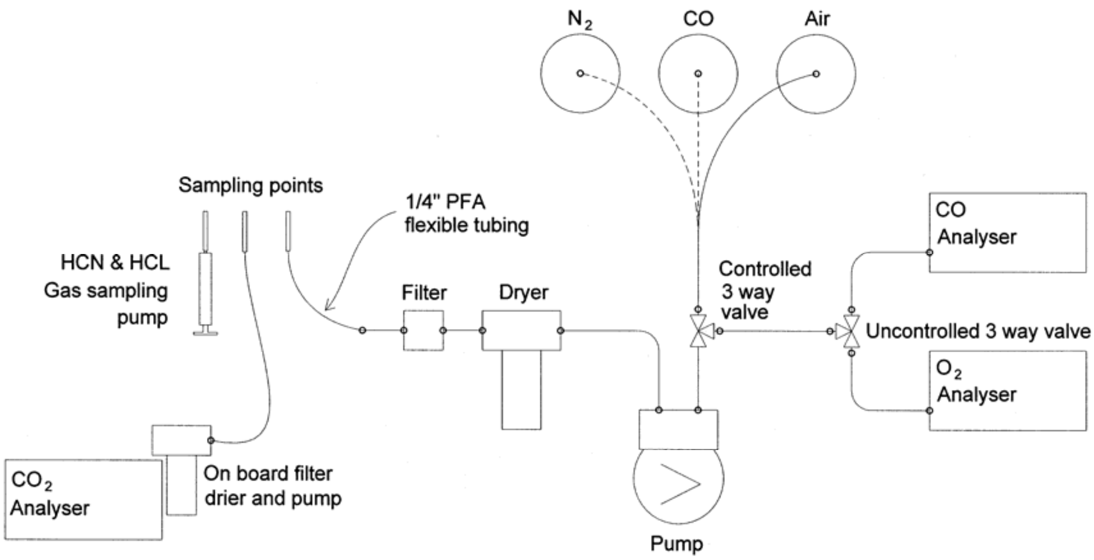


Figure 5.6.1: Schematic diagram of gas sampling system

5.6.2. Carbon Monoxide

Carbon monoxide was measured using a non-dispersive infrared (NDIR) gas analyser. A highly selective infrared detector unit receives low energy infrared radiation from a hot wire source within the analyser. The detector unit is filled with a pure sample of carbon monoxide and therefore can respond only to energy in that region of the infrared spectrum corresponding to the unique absorption band of carbon monoxide.

When the gas to be measured enters the analyser it passes through a cell in the path between the radiation source and the detector. The sampled gas absorbs some of the radiation, according to the concentration of CO present, and thus reduces the level of energy reaching the detector. This change in energy is amplified to provide the analyser with an output signal corresponding to a concentration of carbon monoxide within the sampled gas.

The CO analyser used in these experiments was manufactured by the Analytical Development Company (see Appendix C for technical specifications). It measured the concentration of CO in the range of 0 - 10% with an accuracy of ± 1%. The sampling rate was set at 0.8 l/min. The linear output signal was 0 - 10 volts.

The CO analyser was connected to a data logger via a terminal block that reduced the maximum output signal from 10 volts to 2.5 volts (see Appendix C for technical specifications). The data logger was attached to a desktop PC and the output recorded at 1 second intervals on PicoLog software. This software allowed the recorded data to be imported into a spreadsheet for processing.

The CO analyser was calibrated before each test. The zero gas was instrument grade nitrogen, and the span gas 8.5% CO in instrument grade nitrogen. The span gas composition was certified to Beta Standard (prepared by volumetric or weighing methods). To maintain stability, the analyser was left running continuously during the testing period.

5.6.3. Oxygen

Oxygen was measured with an analyser containing a paramagnetic transducer. Paramagnetism is the property of oxygen that distinguishes it from most other common gases. The transducer incorporates an optical system that contains a mirror attached to a suspension mechanism. This mechanism responds to the concentration of oxygen surrounding it, reflecting light from a light emitting diode onto a split photocell. As the oxygen concentration changes, the light received by each side of the photocell (and therefore its differential output) also changes. Supporting circuitry converts the differential output into a signal proportional to the oxygen concentration.

The O_2 analyser used during these experiments was manufactured by Servomex (see Appendix C for technical specifications). It measured the concentration of oxygen in the range of 0 - 100%, with an accuracy of ± 0.02% O_2 or 1% fsd, whichever is the greater number. The maximum sampling rate was 250 ml per minute. The linear output signal ranged from 0 - 10 volts.

The O_2 analyser was connected to a data logger via a terminal block that reduced the maximum output signal from 10 volts to 2.5 volts. The data logger was attached to a desktop PC and the output recorded at 1 second intervals on PicoLog software. This software allowed the recorded data to be imported into a spreadsheet for processing.

The O_2 analyser was calibrated before each test. The zero gas was instrument grade nitrogen, and the span gas was standard dry air (i.e. 20.96% O_2). To maintain stability, the analyser was left running continuously during the testing regime.

5.6.4. Carbon Dioxide

Carbon dioxide was measured using a non-dispersive infrared (NDIR) gas analyser. This analyser operates in the same manner as the CO analyser, except that the detector unit is filled with a pure sample of CO_2 rather than CO, and therefore responds only to energy in that region of the infrared spectrum corresponding to the absorption band of carbon dioxide.

CO_2 was measured during the experiments using a portable multi gas analyser manufactured by Autodiagnostics Limited (see Appendix C for technical specifications). Although the analyser was capable of being connected to a data logger to record the output, compatible software could not be obtained at the time of the research.

Fortunately the analyser had an LCD display on the front of the unit, and so a digital video camera was used to record the output from the display in real time during each test. The data was then transcribed from the video footage into a spreadsheet at 10 second intervals.

The CO_2 analyser performs zero checks at 30 minute intervals using air drawn in through the rear of the unit, and if necessary will self calibrate. Alert messages are displayed for the user if any calibration or operation fault is detected. In order to reduce the possibility of contaminated air affecting the calibration, sampled gas was exhausted from the analyser some distance from the rear of the unit via a length of tubing. For this reason the analyser was also located some distance from the CO and O_2 analysers. The analyser calibration had been set using Beta Standard span gas containing 10% CO_2. The analyser was considered sufficiently stable that a span gas calibration was only required periodically [47]. The analyser was not calibrated with a span gas during the testing.

5.6.5. Hydrogen Cyanide and Hydrogen Chloride

Discrete grab samples of HCN and HCl were taken using detector tubes and a manual sampling pump manufactured by Gastec (see Appendix C for technical specifications). A tube containing a detecting reagent that is sensitive to the target substance is fitted to the end of the manual sampling pump. The gas sample is then drawn through the tube over a prescribed time interval. The reagent will change colour in response to the presence of the target substance. The tube has graduated markings printed on the outside, and the extent of colour change of the reagent can be used to determine the concentration of the target substance in the sample.

The hydrogen cyanide detection tubes (No. 12M) were used with a 1 minute sampling time. This provided a measurement range of 50 to 800 ppm, with a relative standard deviation of 10% for 50 to 200 ppm, and 5% for 200 to 800 ppm. The hydrogen chloride detection tubes (No. 14M) had a measuring range of 20 to 500 ppm. The relative standard deviation was 10% for 20 to 100 ppm, and 5% for 100 to 500 ppm.

5.7. Visual Obscuration

As with the gas sampling, visual obscuration measurements were taken at two heights, 800 mm and 1600 mm above floor level. Again as per the gas sampling, measurements were taken at only one height during each test. To enable comparison of results, the visual obscuration measurements were always taken at the same height as the gas sampling in any given test.

Visual obscuration was measured using a laser transmitter that generated a red laser beam at a wavelength of 650 nm. The beam was received by a planar photodiode operating in photovoltaic mode. The diode produced a linear voltage output in response to irradiance from the laser. The diode had a spectral sensitivity range of 400 - 700 nm, with maximum sensitivity at a wavelength of 550 nm. The signal output range was 0 - 9 volts.

The photodiode receiver was connected to a data logger via a terminal block that reduced the maximum output signal from 10 volts to 2.5 volts. The data logger was attached to a desktop PC and the output recorded at 1 second intervals on PicoLog software. This software allowed the recorded data to be imported into a spreadsheet for processing.

The both the laser transmitter and photodiode receiver were housed in separate metal boxes with a small penetration in each to allow the laser beam to pass through. To further protect the instruments and integrity of the output, a small piece of gypsum plasterboard was placed over each of the two boxes, extending approximately 200 mm in front of each in an attempt to prevent spray from the sprinkler entering the units.

The two units were fixed firmly to a rigid support member such that the laser transmitter and receiving diode were exactly 1.0 metres apart horizontally. The boxes were located half way along the compartment, 430 mm out from the wall (see Figure 5.2.1 and Figure 5.2.2). This placed them in close proximity to the gas sampling points.

5.8. Temperature

Compartment temperature was measured using 1.5 mm solder tipped, fibreglass insulated Type K thermocouple wire. A vertical loom containing 8 thermocouples was located in the centre of the compartment (see Figure 5.2.1). The thermocouples were spaced 300 mm apart, with the top most thermocouple positioned 150 mm below the ceiling and the bottom most thermocouple 150 mm above floor level. Positioning the thermocouples in the centre of the compartment gave an average temperature profile within the room. It did not provide information on the temperature in close proximity to the fire, or at the sprinkler heads.

The thermocouples were connected to an 8 channel thermocouple data logger (see Appendix C for technical specifications). The thermocouple logger was attached to a desktop PC and the output recorded at 1 second intervals on PicoLog software. This software allowed the recorded data to be imported into a spreadsheet for processing.

5.9. Mass Loss

Mass lost from the burning television sets was measured using a set of electronic scales and indicator unit manufactured by Mettler Toledo (see Appendix C for technical specifications). The scales had a range of 0 - 150 kg, with an increment of 0.005 kg. A laptop computer connected to the indicator unit recorded the output, in kilograms, using HyperTerminal software. The data output rate averaged 13.84 weigh values per second. The HyperTerminal software allowed the data to be imported to a spreadsheet for processing.

The scales were placed inside a series of shallow aluminium boxes to protect them from damage (see Figure 5.9.1). Two layers of gypsum plasterboard were placed between the television set and the top of the aluminium box, and another layer between the box and the scales to protect the scales from conducted heat.

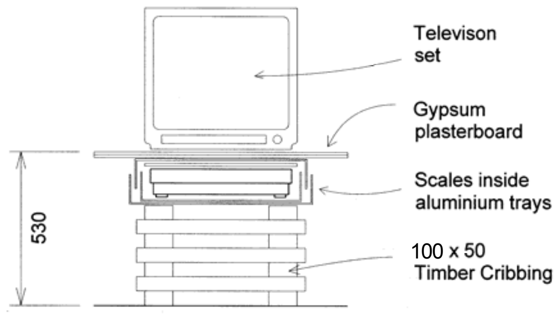


Figure 5.9.1: Fuel load and mass loss measurement configuration

5.10. Video Footage

A digital video camera was located 800 mm above floor level behind one of the observation windows facing the corner of the compartment in which the television sets were positioned (see Figure 5.2.1). The camera was fitted with a 30° wide angle lens, and provided a visual and audio record of fire development during each of the tests.

5.11. Fuel Load

Television sets manufactured for the New Zealand market are required to comply with AS/NZS 60065:2003 [18], in which the safety requirements for audio visual equipment and similar electronic devices are detailed. This standard is based on the European standard IEC 65 (EN 60065) which means that television casings must meet the HB rating in accordance with UL 94.

The television sets used as the fuel load in these tests were acquired from electrical appliance repair outlets. These were sets that had been brought in to the store for repair, but upon examination were found to be irreparable. Acquiring sets in this manner meant that all the televisions had been used, and were of varying age and condition.

No attempt was made to place any selection criteria on the sets, other than that the televisions had to be intact, and preferably of the same size. As it turned out, it was not possible to obtain a sufficient number of identically sized sets, and so the televisions used in the tests ranged from 20 inch to 29 inch.

The sets were gathered at random from a number of repair shops over the months preceding the experiments. In all 22 fully intact television sets were obtained. Although not substantiated statistically, it is reasonable to assume that the televisions used for these tests were representative of those typically found in New Zealand homes.

It is important to note that the selection included three pairs of virtually identical sets. Tests 4 and 16 involved the same Philips model, Tests 8 and 20 involved the same Sony model, and Tests 14 and 18 involved the same Transonic model. This may have implications for any statistical analysis drawn from the results of the tests.

All the television sets used in the tests had plastic outer casings. Often the material surrounding the front of the sets differed from that enclosing the rear portion. It has been assumed that this is for aesthetic reasons since the rear section of the set is not readily visible, and therefore not required to have a high quality finish. From information provided in previous studies [16,19,25] it has been assumed that the outer casing is made of high impact polystyrene. The television sets used are described in Table 5.11.1.

It should be noted that another 29 inch Philips television was also tested, however the internal circuitry in this set had been completely removed. Even though it is recognised that the majority of the fuel load is comprised of the plastic casing, for the sake of consistency this set was not included in the analysis. Manufacturing information for all sets is included in Appendix D.

The television sets were placed in the rear corner of the compartment opposite the door (see Figure 5.2.1). It should be noted that in the UL 1626 residential sprinkler test compartment, the fuel load is placed diagonally opposite the opposing door (see Appendix B). The decision to place the fuel load in line with the door was made to facilitate manual extinguishment operations after each test. The person entering the compartment to carry out firefighting could use the side wall to way find, and would not risk damaging the thermocouple tree or visual obscuration measurement devices in the process.

The television sets where placed on top of 2 sheets of 10 mm gypsum plasterboard over a series of aluminium trays housing the electronic scales. The trays containing the scales were in turn sitting on 100 x 50 mm timber cribbing to provide a stable elevated platform (see Figure 5.9.1). This placed the base of the television sets at a height of 500 mm above the floor level. The height and corner location of the television sets provided a realistic approximation of what might be found in a typical apartment living space.

It is important to note that this fuel configuration represents a worst case scenario in that the TV set is the only combustible item in the vicinity. It can be argued that in a realistic living room, it would expected that video tapes, curtains and even the entertainment cabinet in/on which the TV is located might accelerate the fire growth rate and produce a faster response from the sprinkler system. Nevertheless, studies suggest that between 30 - 40 percent of television fires do not spread beyond the TV set [20,26], so isolating on a non-combustible stand does not represent an unrealistic scenario.

Burning the television set in isolation also has the advantage of reducing the number of variables. The complex geometry of a television set and combination of construction materials will make heat release analysis difficult enough without introducing any other fuel packages.

Table 5.11.1: Description of television sets used during tests

Test No.	Make	Model	Size
0	Philips	25GR6771/79R	25 inch
1	Mitsubishi	CT-25AM2	25 inch
2	Panasonic	CN218RVQ	21 inch
3	Sony	VX/15	21 inch
4	Philips	20CT636/79R	20 inch
5	Toshiba	2132DB	21 inch
6	Panasonic	TC-20L32	20 inch
7	Sanyo	C25ZG51	25 inch
8	Sony	KV-T25SF11	25 inch
9	Goldstar	CF-20A74	20 inch
10	Philips	21GR1369/79R	21 inch
11	Toshiba	207R9A	20 inch
12	Sony	KV-2153 SN	21 inch
13	Mitsubishi	CT-2148NZM	21 inch
14	Transonic	CTV-5144	20 inch
15	Sanyo	CZP2141TXA-00	21 inch
16	Philips	20GR1250/79R	20 inch
17	Sanyo	C29ZK80TX-51	29 inch
18	Transonic	CTV-5144	20 inch
19	Samsung	CB-681 3WT	25 inch
20	Sony	KV-T25SF81	25 inch
21	Transonic	GT-8828	29 inch

5.12. Ignition Method

The aim of these experiments was to analyse the tenability conditions arising from a television fire within the compartment. The exact method by which the television set was ignited was not critical to the outcome of the research. The two potential ignition sources for a television set are internal, and external. Internal ignition could be expected from an electrical fault within the componentry of the set, most likely associated with the power supply.

External ignition could come from a number of sources, but is most likely to result from an open flame impinging on the television casing. Previous studies have indicated that the between 20 - 40 percent of television fires result from an external ignition source [20,26]. In order to make the ignition process as simple and consistent as possible, a tea light candle was used to provide an external ignition source during the tests.

Double wicked tea light candle

Typical location at rear of TV casing using single wicked tea light candle

Figure 5.12.1: Ignition sources and location

Variations in both the physical shape, and the ignition properties, of the outer casings of the television sets meant that it was not possible to use a single ignition method during the tests. Instead a sequential ignition process was adopted until self-sustaining combustion of the outer casing was achieved.

This sequential process recognised the fact that the material comprising the front part of the casing was frequently easier to ignite than the material encasing the rear part of the television. The ignition process followed during these tests is outlined in Table 5.12.1. An example of a double wicked tea light candle is shown in Figure 5.12.1 along with a typical location for the ignition source at the rear of the TV set.

Where possible, initial ignition was attempted in each test using Method 1. This provided a heat release of approximately 30 W [16]. If self-sustaining combustion was not evident within the prescribed duration, the next method was implemented until all four methods had been attempted. If ignition had not occurred after the prescribed duration for Method 4, the test was terminated.

Table 5.12.1: Sequential ignition process for television fires

Method	Description	Duration
1	Tea light candle placed at base level under overhanging portion of outer casing at left rear corner of television, when facing screen	10 min
2	Single match stick placed horizontally across top surface of the candle positioned as per Method 1 to provide increased surface area for flame (double wick effect)	10 min
3	Tea light candle placed at base level under overhanging portion of outer casing at left front corner of television, when facing screen	10 min
4	Single match stick placed horizontally across top surface of the candle positioned as per Method 2 to provide increased surface area for flame (double wick effect)	10 min

Although not central to the research objective, the sequential ignition process did provide some insight into the inherent ease of ignition of each set, including differences between the front and rear casings. While all the sets were expected to perform to the HB rating, there was still a degree of variation in the ignition properties of the different sets. Out of interest this information is included in the results. It should be noted that the shape of individual sets meant that it was not always possible to follow the sequence, or position the candle exactly as detailed for a particular method. Where this occurs, it has also been noted in the results.

For the purposes of establishing a timeline, each test was considered to have commenced (i.e. $t = 0$) at the start of the successful ignition method. This methodology may have resulted in minor changes to ambient conditions from previous ignition attempts, particularly with regard to smoke and fire detector counts. Where noticeable changes were observed, the compartment was aired before restarting the test using the next ignition method in the sequence.

6. Data Processing

While some of the data recorded during the tests could be used directly in the analysis, such as smoke and fire detector counts and thermocouple temperatures, other data had to be processed first.

6.1. Carbon Monoxide and Oxygen

The output from both the CO and O_2 analysers expressed the gas concentrations (in percentage volume) as a voltage. In order to carry out FED calculations, this information had to be converted back into concentrations and expressed as a percentage for O_2, and parts per million (ppm) for CO (see Equations 4.1.3 and 4.1.5).

Since the voltage output formed a linear relationship with the measured gas concentration, converting the output signal into a concentration was relatively simple. Once the voltage at two known gas concentrations was found, a process of linear interpolation or extrapolation could be used to determine the concentration for any given voltage.

The calibration process provided a known concentration of 0% for both gases, and 8.5 % and 20.96 % for CO and O_2 respectively. Since the concentrations of each gas during the tests are not expected to exceed these span gas concentrations, the conversion will be interpolative rather than extrapolative. This reduces the error margin since any measurement error associated with the analyser will not be amplified by extrapolating the results.

During the calibration procedure the output signal from each analyser was recorded for 120 seconds. This reading was averaged, and the resulting value used in the interpolation process. The percentage volume of CO was multiplied by 10,000 to convert it to parts per million.

6.2. Carbon Dioxide

The FED calculation required the concentration of CO_2 as a volume percentage (see Equation 4.1.4). While the analyser provided the CO_2 concentration directly as a percentage on the output display screen, the information could only be captured on video tape. This data was subsequently transferred to a spreadsheet in 10 second intervals.

However the data from the other two gases was recorded at 1 second intervals, and therefore this time step was adopted in the FED calculations. To make the CO_2 data compatible it was converted into 1 second time steps by using the value from each 10 second reading in the following nine 1 second intervals. This method was considered valid as the concentration of CO_2 did not alter dramatically over each 10 second interval, and therefore a more complicated interpolation method was not deemed necessary.

6.3. Visual Obscuration

The photovoltaic receiver measuring visual obscuration expressed the level of irradiance received from the laser transmitter as a voltage. As with the CO and O_2 analysers, the relationship of measurement to output signal was linear. In order to calculate optical density per metre, the intensity of incident light and the intensity of light through the smoke are required (see Equation 4.2.1). Since the equation expresses these two values as a ratio, the output can be used as a voltage. The output signal from the photovoltaic receiver was recorded for a period of 120 seconds prior to each test commencing. The average recorded value over this 120 second interval was used as the intensity of incident light I_o. This process was repeated for each test, because minor variations in alignment between transmitter and receiver altered the voltage reading. As both the transmitter and receiver were removed regularly for cleaning, achieving identical ambient readings from test to test was not possible.

It should be noted that variations in the ambient readings would alter the error margin from test to test. However the results revealed that the rate of change in OD/m at the time the tenability threshold was exceeded was generally so great that any variation in accuracy would be of minor consequence. The intensity of light through the smoke *I*, was given by the voltage output from the receiver for every time step during the test.

6.4. Mass Loss

This was the data that needed the most processing to arrive at a useful result. Mass loss information was required in order to calculate the heat release rate of the fire during each test (see Equation 4.4.1). Although the output from the scales was expressed in kilograms as required in the calculation, the scales recorded the mass at a rate of 13.84 outputs per second. This figure was determined empirically by logging data from the scales over a defined time period and counting the number of outputs recorded.

The high data capture rate created a lot of 'noise' when the resulting heat release rate was expressed graphically. In order to smooth the graph a moving average for each time step of mass data had to be taken. This process was made difficult because the sensitivity of the scales was restricted to 0.005 kg and change in mass over short time periods throughout each test was often smaller than this value. Therefore to get a useful value, the moving average was taken over a 20 second time period.

Once the moving average of the mass for each time step had been determined, the mass loss rate could be calculated. In a further attempt to smooth out the graph, the mass loss rate was calculated over 5 second intervals. This value was then divided by 5 to give an approximation of the mass loss rate $\dot{m}$ in kilograms per second, as required by the HRR equation.

It is important to note that the intermediate data needed further manipulation to account for sudden changes in mass not associated with mass loss in the combustion process. For example there were occasions when melting plastic from the television casing ran off the edge of the weighing assembly, and other occasions when pieces of the television fell off as the set burned. This is doubly problematic in that the pieces which fell off the weighing assembly may have continued to burn, contributing to the overall HRR in a manner that could not be measured. As a result the mass loss data used to estimate the HRR is not a completely accurate record of the mass lost to burning during each test, but rather represents a best approximation.

Once a suitable mass loss rate $\dot{m}$ was found, it was multiplied by the effective heat of combustion to provide the heat release rate. An effective heat of combustion of 30 MJ/kg was assumed for the non-fire retarded high impact polystyrene television set enclosures. This figure was based on information provided by Babraskas [19] but once again, because there are likely to be variations between each set tested, this represents a best approximation only. Care must therefore be taken when assessing the HRR results based on this methodology.

7. Results

22 television sets were used during these experiments (see Table 5.11.1). Test 0 was used as a trial run with a non-standard ignition method and therefore has not been included in the results. When a test resulted in the activation of a sprinkler head, the sprinkler was left on for 1 to 2 minutes before being shut off to prevent flooding of the facility.

Where possible data was captured for a further 2 minutes after the sprinkler was shut off, however since shutting off the sprinkler affected conditions within the compartment, this information has not been used in the results. Graphs contained in the main body of this report show a run time up until sprinkler shut off, whereas graphs contained in the appendices show the full range of data, with the sprinkler shut off time marked on the graph.

While the ultimate decision as to whether an occupant could escape safely from the apartment is determined by the FED for asphyxiant gases, the assessment relied on the results of the fire safety system and other tenability measurements as well. Therefore the results and discussion will focus on these other measurements first, and culminate in an analysis of the ability to evacuate based on the FED.

7.1. Ignition Method

Although the main focus of this research was on the consequences of a television fire in the apartment, information on the ignitability of the sets provides some insight into the probability of this type of fire occurring in the first place. The information on the ignition methods used for each test is contained in Table 7.1.3. In each of the tests the television set was successfully ignited, with the exception of Test 19. This implies that the sets used were not fire retardant, in that they did not meet the V-0 rating under UL 94. This is consistent with the requirements of AS/NZS 60065:2003, which only requires television sets manufactured for the New Zealand market to meet the HB rating under UL 94, rather than the more stringent V-0 classification.

Despite the fact that the majority of the casings did not appear to contain any fire retardant additives (i.e. bromine), variations in the material properties of each set meant that they did not display a uniform ease of ignition. Figure 7.1.1 shows the results of the tests by ignition method. With this information it is possible to assign an ignition characteristic to each set. If a set is ignited using Method 1, then its ignitability can be considered to be 'very easy'. If on the other hand Method 4 is required to achieve ignition, then it can be considered 'hard'. This characterisation assumes that the front part of the TV enclosure will be no harder to ignite than the rear part i.e. if the rear casing can be ignited with a single wick, then so can the front.

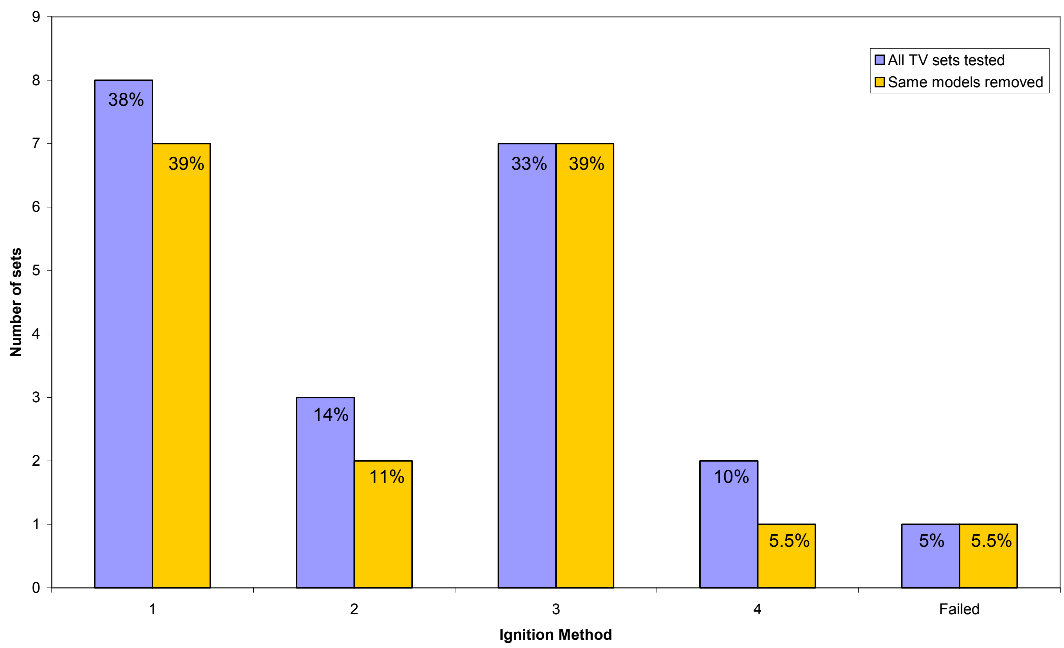


Figure 7.1.1: Comparison of ignition methods

Assessing Methods 2 and 3 is somewhat harder, however Method 3 is considered more onerous on the basis that if the rear casing cannot be ignited, then the set will not be as susceptible to an internal ignition source. The front part of the casing would also present a smaller target area for an external ignition source, although it might be argued that the majority of external ignition sources, e.g. candles, would be concentrated at the front of the set. It should be noted that this assessment is strictly qualitative and only serves to give a broad indication of the ignition properties of each set.

Employing these subjective criteria on the test results reveals that 38 percent of the sets were easy to ignite, a further 47 percent easy/moderate, and only 10 percent of the televisions were truly difficult to ignite. 5 percent, represented by a single set, could not be ignited using the test methodology.

Table 7.1.1: Ignition characteristics of test sets

Method	Number	Percentage	Ignitability
1	8	38	Very easy
2	3	14	Easy
3	7	33	Moderate
4	2	10	Hard
5	1	5	Very hard

It should be noted however that the test sample included 3 pairs of the same model television, and is therefore not necessarily statistically valid. It should be recognised however that as there was no statistical methodology employed in the collection of the televisions in the first place, removing the identical sets would not produce a more representative statistical model for televisions used in New Zealand. Nevertheless, removing the identical sets will allow an unbiased analysis of the different sets used in the sample. Tests 4 and 16 used the same model of TV set, as did Tests 8 and 20, and Tests 14 and 18.

Interestingly, the ignition results in Table 7.1.3 reveal that in only one of these three cases was the same ignition method successful (Tests 14 and 18). This implies that either the uncertainty associated with achieving sustained combustion by each ignition method was greater than the time period allowed for that method, or that there may be some variation in the manufacturing process between different batches of the same set model effecting ignitability. To be conservative, where variation occurs, the lower numbered ignition method has been assigned to the set. The ignition results for the 18 sets used in this adjusted analysis are contained below in Table 7.1.2.

Table 7.1.2: Ignition characteristics of different model test sets

Method	Number	Percentage	Ignitability
1	7	39	Very easy
2	2	11	Easy
3	7	39	Moderate
4	1	5.5	Hard
5	1	5.5	Very hard

Table 7.1.3: Sequential ignition procedure results

Test	Method 1	Method 2	Method 3	Method 4	Comments
1	✗	✗	✓		
2	✗	✗	✗	✓	
3	✗	✓			
4	✗	✓			
5	✓				
6	✗	✗	✓		
7	-	-	✓		Not possible to locate candle at rear of casing
8	✗	✗	✗	✓	
9	✓				
10	✓				
11	-	-	✓		Not possible to locate candle at rear of casing
12	✗	✓			
13	✗	✗	✓		
14	✓				Candle set towards the front of rear casing
15	✓				Candle set towards the front of rear casing
16	✓				
17	✗	✗	✓		
18	✓				Candle set towards the front of rear casing
19	✗	✗	✗	✗	Television could not be ignited
20	✗	✗	✓		
21	✓				Candle set towards the front of rear casing

- : Not attempted

7.2. General Observations

In most of the tests the plastic casing took some time to achieve sustained combustion, however once self-sustaining combustion occurred the fire generally progressed in a steady manner. The smoke given off in the initial stages following sustained combustion was typically light grey or white in colour. As the fire grew, the smoke became thicker and changed to a dark grey colour.

A clearly defined smoke layer formed at the ceiling of the compartment and descended in a fairly uniform manner (see Figure 7.2.1). Stringy ‘polymers’ of up to 50 mm in length were observed in the smoke layer. These soot strands, presumably polystyrene, were heavier than the other solid particulates and dropped out of the smoke layer to settle on the floor of the compartment.

In most cases the plastic TV enclosure in the vicinity of the pilot flame began to melt almost immediately, with flaming drops falling onto the gypsum support platform. Once the fire was well established, melting plastic formed a pool fire at the base of the set and contributed to the speed of fire development. On occasion the pool of melted plastic would run off the side of the support platform. This would result in a mass loss measurement not associated with burning fuel. On other occasions pieces of the television set would fall to the ground, causing abrupt changes in mass measurement. If these fallen pieces continued to burn on the ground, then the actual heat release rate would be greater than that shown by the mass loss data.

At intervals during the fire parts of the internal electronic circuitry exploded with a loud popping noise. This noise may have been sufficient to attract the attention of an occupant asleep in an adjoining bedroom. Since the cathode ray tube in a television set is vacuum sealed, most tubes imploded at some point in the fire. In one case (Test 13), the tube exploded violently, showering the compartment with glass.

The determining factor in whether the fire would result in sprinkler activation or not appeared to be the time at which the descending smoke layer reached the base of the television set. Visual observations indicated that the descending smoke layer had a vitiating effect on the fire, with the resulting reduction in oxygen supply limiting the heat release rate. Therefore if the sprinkler had not activated before the smoke layer enveloped the burning TV, it was likely that the television would be unable to produce sufficient heat to activate the sprinkler during the remainder of the test. The general availability of oxygen within the compartment (other than the effect created by the descending smoke layer) did not appear to a limiting factor on fire development.

If the sprinkler did not activate, then the smoke layer would eventually reach ground level and the inside of the compartment would be reduced to complete blackness. In these conditions, the fire was not visible from the observation window 4 m away. Post fire investigation showed that this was not caused by excessive carbonaceous deposits on the inside of the windowpane. By the end of the tests in which the sprinkler did not operate, the fire had consumed virtually all of the plastic casing.

Burning TV set and smoke layer

Screen shields rear casing from sprinkler discharge

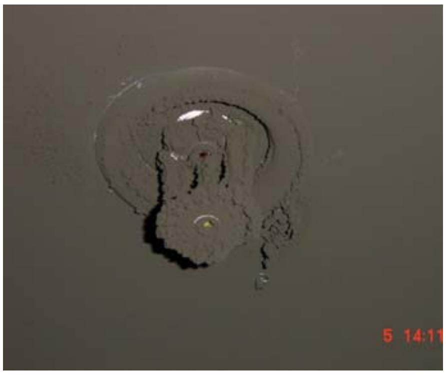
Figure 7.2.1: Smoke layering and sprinkler shielding

In the tests where the sprinkler did operate, the thermal balance in the compartment was immediately disrupted, resulting in a rapid loss of visibility as the smoke was dragged down into the lower parts of the compartment (see Figure 7.4.2). The inside of the compartment was generally blacked out completely within 10 to 20 seconds of sprinkler activation. The level of smoke obscuration did not noticeably change during the 1 - 2 minute sprinkler discharge period.

It should be noted that the 1 - 2 minutes of sprinkler discharge never completely extinguished the fire, which generally started to grow again as soon as the sprinkler was shut off. Part of the explanation for this could be that the sprinkler system was operating at a flow rate below the minimum specified by the manufacturer. However another significant contributing factor was that the non-combustible screen of the TV formed a very effective shield that prevented a large portion of the discharge spray from reaching the burning plastic case behind it.

When the door to the compartment was opened, large quantities of heavy, dark smoke immediately discharged through the doorway (see Figure 7.2.2). This occurred irrespective of whether the sprinkler had operated. Had the door been connected to another space, such as a bedroom, this adjoining room would have rapidly filled with smoke. An occupant exiting the bedroom would have very limited time in which to react before being exposed to the full effects of the smoke.

Smoke generation at end of test



Soot deposits on sprinkler head (Test 20)

Figure 7.2.2: Smoke and soot generation during tests

A significant quantity of sooty deposits accumulated on the inside surfaces of the compartment during each test, particularly during the longer tests and those in which the sprinkler did not activate. Figure 7.2.2 shows the carbonaceous material that had built up on the sprinkler head closest to the fire (Sprinkler 1) in Test 20 by the end of the test. It is worth noting that this particulate deposit may have contributed to the sprinkler not activating by forming an insulating layer around the heat sensitive glass bulb. At the very least the quantity of soot within the compartment is indicative of the sensory and respiratory irritation that might be expected from this environment.

7.3. Fire Safety Systems

The response of the various analogue smoke and fire detectors was recorded continuously over the duration of each test. The activation time of the sprinkler system was also recorded for each test. Graphs for each test are contained in Appendix E, and a typical example is shown in Figure 7.3.1.

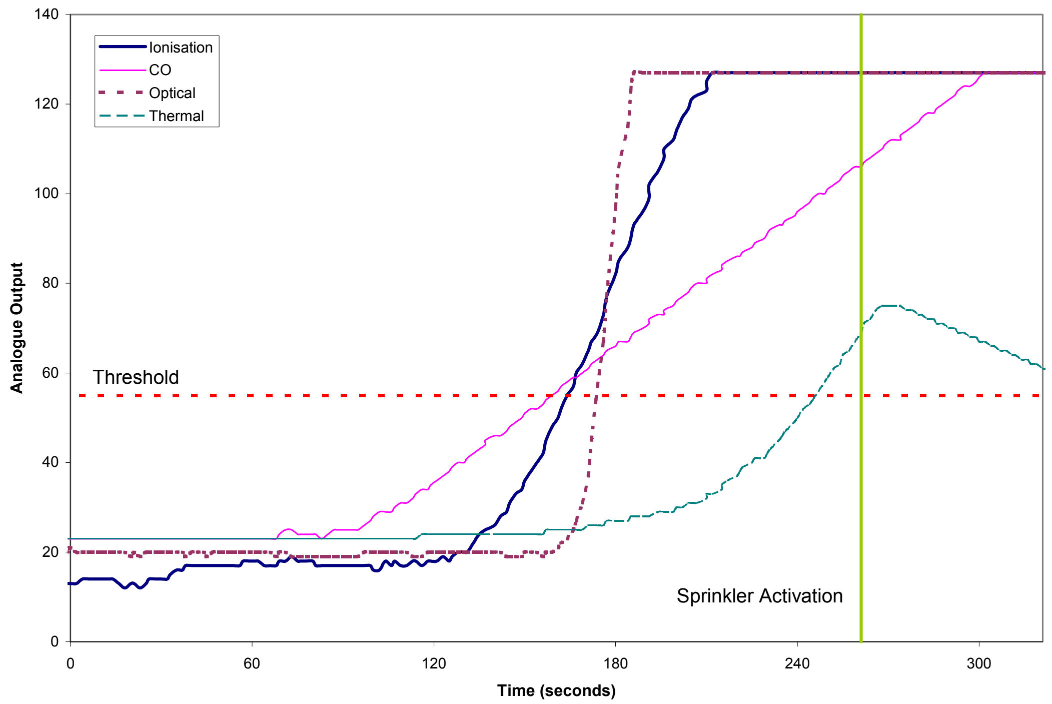


Figure 7.3.1: Fire safety system response (Test 4 - Compartment)

The primary objective of the research is to compare the ability of each system to provide warning of fire. As such the actual activation time is more important than the responsiveness of the system. Activation times for each system in each test are contained in Table 7.3.1. This information is perhaps better presented in the bar graphs contained in Figure 7.3.2 and Figure 7.3.3. The data is displayed on two graphs for visual clarity. This separation is also convenient because no detection data was available for Tests 10 - 12, and lobby detection was not installed until Test 13.

Although the timeline would traditionally follow the horizontal axis, in this case it has been located on the vertical axis to allow the use of larger bars. It should be noted that where the bars for a particular system extend over the maximum time, this indicates that the system did not activate during the relevant test. Missing bars indicate that the detector was not functioning during a particular test, apart from Test 19 where the set could not be ignited. In all the tests except one where the sprinkler activated, only the sprinkler closest to the fire (Sprinkler 1) operated. The exception was Test 3, in which the second sprinkler also activated subsequent to Sprinkler 1 operating.

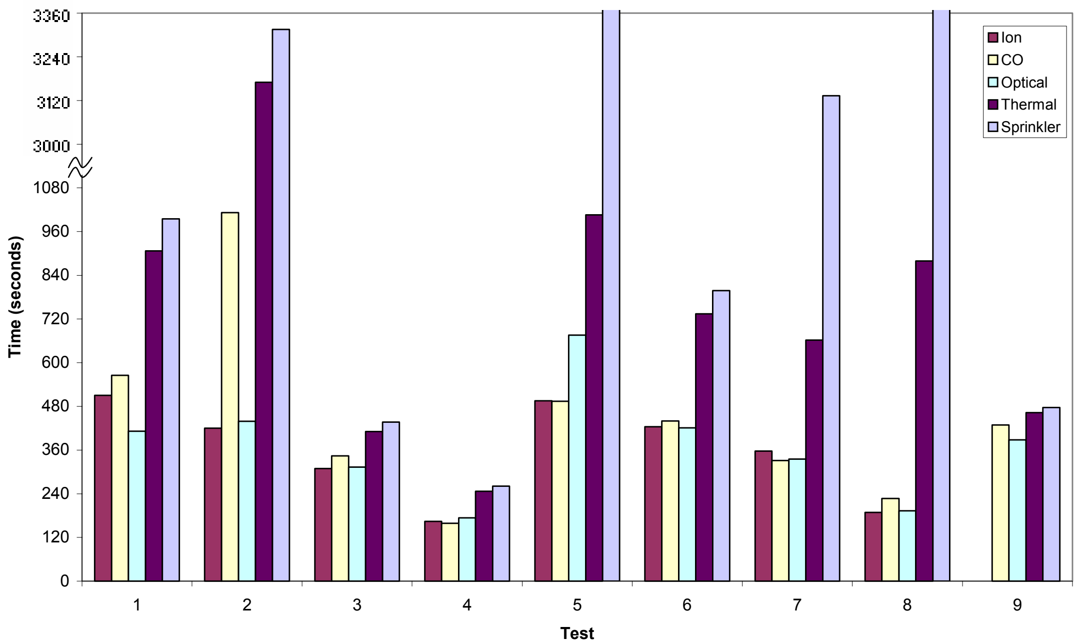


Figure 7.3.2: Fire safety system activation times (Tests 1 – 9)

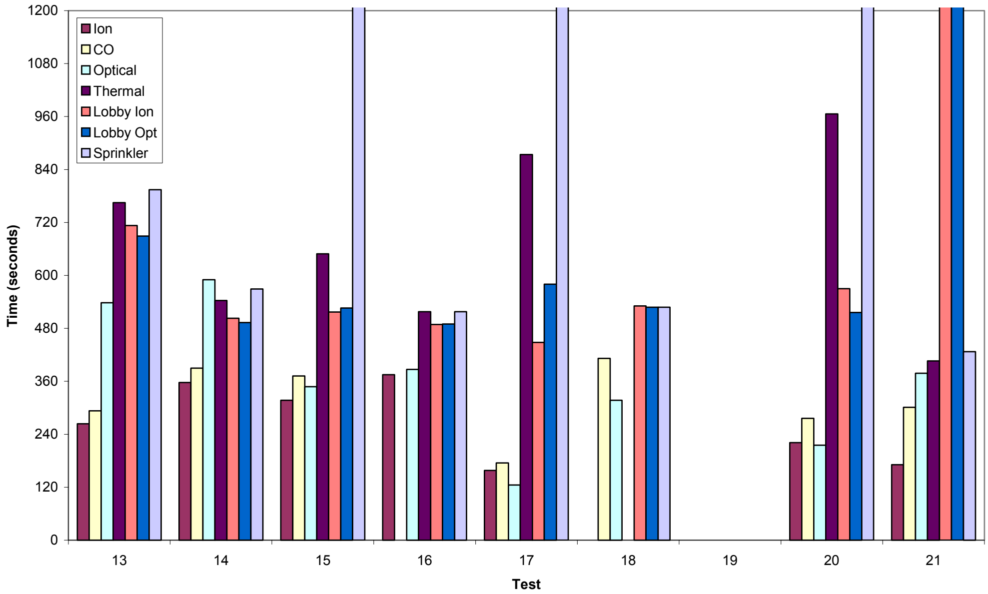


Figure 7.3.3: Fire safety system activation times (Tests 13 – 21)

The data contained in Table 7.3.1 allowed the performance of each detection system to be compared to every other detection system over all the tests. For each test the differences in activation times between each system were entered into the analysis program @RISK [48]. The 'BestFit' function in @RISK was used to fit a probability distribution to the difference in activation times between each system. This in turn allowed the response of any two systems to be compared using not only the mean difference in activation time, but also the standard deviation (SD) and degree of skewness. Skewness measures the degree of asymmetry in a distribution. A negative skew number means the distribution has more values to the left of the peak, while a positive skew means the distribution has more values to the right. The BestFit distribution curve and associated data for each comparison are contained in Appendix F, and the results of the comparison between the compartment ionisation detector and the sprinkler system is shown in Figure 7.3.4 below as an example.

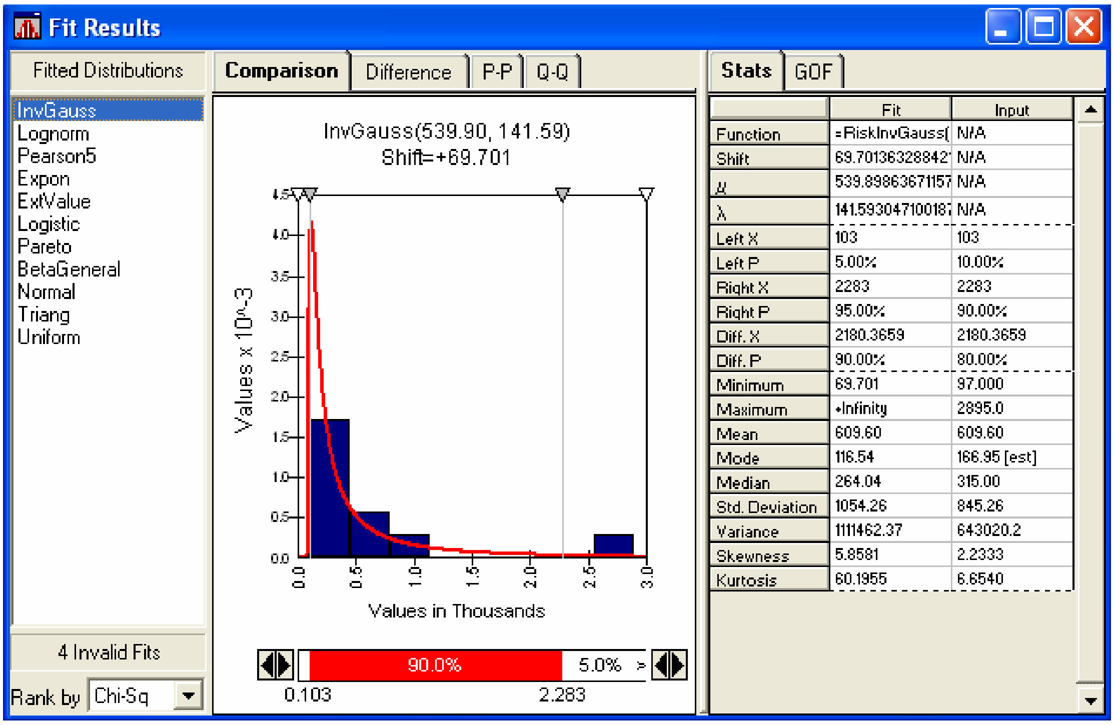


Figure 7.3.4: Distribution of differences in activation times between ionisation detector and sprinkler system

The results of each comparison are summarised in Table 7.3.2. It should be noted that the number of samples in each comparison varied (from 6 to 17) and this will affect the level of certainty associated with each fit. Distribution information for the comparisons between the two lobby detectors and the sprinkler system has not been included as there were only four data points in each of these comparisons. This provided insufficient information for BestFit to construct a distribution. The small sample sizes of the remaining data sets meant that the fit was not particularly strong in any case, and consequently it is difficult to draw any conclusions from comparing the different distributions. Therefore this information is best restricted to nothing more than providing an indication of the nature of the difference in activation times between each system.

There was considerable variation in the response between the two compartment smoke detectors, with a range of 372 seconds. The ionisation detector was on average faster to respond than the optical detector, with a mean response time difference of 54 seconds. The results show that the CO detector response was on average slower than either of the smoke detectors, although not significantly (less than 90 seconds in either case). The results also show that the mean thermal detector response was significantly slower than either of the two smoke detectors (over 7 minutes slower than the optical detector, and nearly 9 minutes slower than the ionisation detector). As expected, the mean delay in sprinkler activation compared to the smoke detectors was large. The average delay between ionisation detector activation and sprinkler activation was 10 minutes, and the average delay between the optical detector and the sprinkler was 8 minutes.

Both of the lobby smoke detectors performed better than the thermal detector in the compartment and, in general, better than the sprinkler system. The lobby ionisation detector activated on average 180 seconds earlier than the thermal detector, and the lobby optical detector activated on average 100 seconds earlier. In comparison to the sprinkler activation times the delay was much less significant, at under a minute for both lobby detectors. In Test 18 the sprinkler activated at the same time as the lobby optical detector, and 3 seconds quicker than the lobby ionisation detector. In Test 21 neither of the lobby detectors operated, even after the sprinkler activated. The mean difference in activation time between the thermal detector in the compartment and the sprinkler system was 100 seconds. In Test 16 the thermal detector activated at the same time as the sprinkler.

It should be remembered when making comparisons with the sprinkler systems that in five cases the sprinkler did not operate at all. So while the difference in response between the sprinkler and thermal detector does not appear great, the thermal detector still activated in all 5 tests where the sprinkler failed to do so. In this respect the thermal detector provided significant advantage over the sprinkler in regard to providing warning of the fire, if not necessarily early warning. It is also worth noting that in Test 21, neither of the lobby detectors activated prior to the sprinkler operating.

It is important to note that the detectors were reused over multiple tests, and were therefore susceptible to contamination. Although the heads were removed and cleaned between each test, contamination from previous tests may have had an effect on detector response. For example the results of Test 14 show that the sprinkler operated before the optical detector in the compartment reached the activation threshold. However inspection of the graph in Figure 7.3.5 showing the detector response does not reveal any overt problems with the performance of the optical detector, other than the delay in its response, which may be caused by the fire conditions.

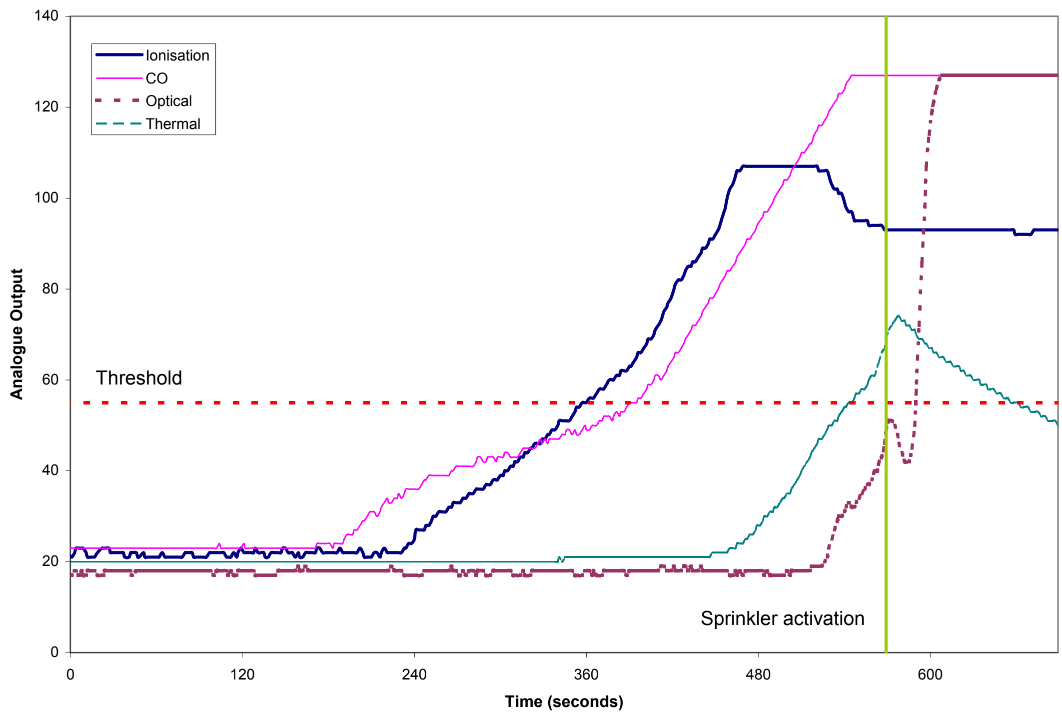


Figure 7.3.5: Fire safety system response (Test 14 – Compartment)

Graphs of the analogue detector outputs for each test are shown graphically in Appendix E, and may provide some assistance when assessing the reliability of a particular detector activation time. Any conclusions drawn from the results of this report however should allow for the possibility of contamination from previous tests effecting detector performance. No attempt has been made to remove potentially flawed results because as the objective of the study is to make a comparative evaluation of available escape time based on alert times provided by smoke detectors and sprinklers, any delays in smoke detector activation only provide an increased level of conservatism to the comparison.

It is worth noting that compartment ionisation detector was replaced with a new head at the start of Test 11 (even though no data was recorded for Tests 10 - 12), and the compartment optical detector was replaced at the start of Test 18 with a slightly used head. On occasion the analogue reading from a particular detector dropped out, either as a result of problems with the detector, or with the logging system. Where these situations have occurred, they are indicated by ‘?’ in Table 7.3.1.

Table 7.3.1: Fire safety system response times (in seconds)

	Compartment				Lobby		
Test	**Ion**	**Optical**	**CO**	**Thermal**	**Ion**	**Optical**	**Sprinkler**
1	510	412	565	907	-	-	995
2	420	439	1012	3170	-	-	3315
3	309	313	344	411	-	-	437
4	164	174	159	247	-	-	261
5	495	676	494	1006	-	-	DNA
6	424	421	440	734	-	-	798
7	357	335	331	662	-	-	1333
8	189	193	227	879	-	-	DNA
9	?	388	429	463	-	-	477
10	-	-	-	-	-	-	434
11	-	-	-	-	-	-	1112
12	-	-	-	-	-	-	217
13	264	538	293	765	713	689	794
14	357	590	390	543	503	493	569
15	317	348	372	649	517	526	DNA
16	375	387	?	518	489	490	518
17	158	125	175	874	448	580	DNA
18	?	317	412	?	531	528	528
19	-	-	-	-	-	-	-
20	221	215	276	966	570	516	DNA
21	171	378	301	406	DNA	DNA	427

DNA : Did Not Activate ? : Problem with output - : No measurement made

Table 7.3.2: Activation time differences between fire safety systems (in seconds)

Comparison	No.	Min.	Max.	Range	Mean	SD	Skew
Opt vs Ion	15	-98	274	372	54	111	0.879
CO vs Ion	14	-26	592	618	73	154	3.015
Thermal vs Ion	15	83	2750	2667	534	651	2.835
Lobby Ion vs Ion	6	114	449	335	258	128	0.328
Lobby Opt vs Ion	6	115	425	310	267	137	0.149
Sprinkler vs Ion	10	97	2895	3140	610	845	2.233
CO vs Opt	16	-245	573	818	22	183	1.457
Thermal vs Opt	17	-47	2731	2778	433	643	2.865
Lobby Ion vs Opt	7	-87	355	442	179	147	-0.605
Lobby Opt vs Opt	7	-97	455	552	186	171	-0.083
Sprinkler vs Opt	12	-21	2876	2897	480	806	2.439
Thermal vs CO	15	34	2158	2124	458	522	2.424
Lobby Ion vs CO	6	113	420	37	227	123	0.501
Lobby Opt vs CO	6	103	405	302	236	136	0.379
Sprinkler vs CO	11	48	2303	2255	478	666	2.095
Lobby Ion vs Thermal	6	-426	-29	397	-179	183	-0.603
Lobby Opt vs Thermal	6	-450	-25	425	-100	167	-0.860
Sprinkler vs Thermal	11	0	671	671	100	194	2.620
Lobby Opt vs Lobby Ion	7	-54	132	186	7	59	1.482
Sprinkler vs Lobby Ion	4	-3	81	84	43	-	-
Sprinkler vs Lobby Opt	4	0	105	105	52	-	-

- : Distribution fit not possible due to small sample size

7.4. Visual Obscuration

One important factor that should be considered in these tests is the impact sprinkler discharge itself will have on visual obscuration, regardless of whether smoke is present in the compartment. It is unlikely that visual obscuration resulting from sprinkler discharge alone would significantly impede an occupant from evacuating the apartment, but it will effect the FEC_{smoke} value. This could result in the FEC_{smoke} threshold being exceeded prematurely. It was therefore considered important to assess the contribution of sprinkler spray to the overall FEC_{smoke}.

No measurements were made during these tests, however visual obscuaration measurements for sprinkler discharge have been carried out in work by Spearpoint et al [49]. In this previous work a maximum visual obscuration reading of approximately 0.09 OD/m for a ‘sprinkler only’ discharge was recorded. Two sprinkler heads were discharging in the compartment, and the recording was made directly under one of the heads. The measurement was taken at a height of 0.66 m above floor level. The model of sprinkler used was a ZX-RES manufactured by Reliable, with a flow rate of 82 l/min.

The value of 0.09 OD/m has therefore been used to approximate the effect of sprinkler discharge on the FEC_{smoke} during this analysis. From Equation 4.2.1 optical density (D) can be defined as:

$$D = \log_{10}\left(\frac{I_o}{I}\right) \tag{7.4.1}$$

This means that the optical density for sprinkler discharge can be subtracted from the total optical density using the following log law:

$$\log_{10}(A) - \log_{10}(B) = \log_{10}\left(\frac{A}{B}\right) \tag{7.4.2}$$

where

$A \quad = \quad \left(\dfrac{I_o}{I}\right)$ *total* (from test measurements)

$B \quad = \quad \left(\dfrac{I_o}{I}\right)$ *sprinkler discharge*

If $D = \log_{10}\left(\dfrac{I_o}{I}\right)$, then $\left(\dfrac{I_o}{I}\right) = 10^D$. In the case of sprinkler discharge $D = 0.09$, therefore $\left(\dfrac{I_o}{I}\right)$ *sprinkler discharge* = 1.23. $\left(\dfrac{I_o}{I}\right)$ *total* can be found directly from the visual obscuration measurements made during the tests.

This adjustment to allow for the effect of sprinkler discharge has been made for each test, except in the cases where the FEC_{smoke} reached its maximum limit prior to sprinkler activation. Visual obscuration measurements were taken in 12 tests where ignition was successful. 9 of the tests involved measurements taken at 800 mm above floor level, the other 3 were taken at 1600 mm above floor level.

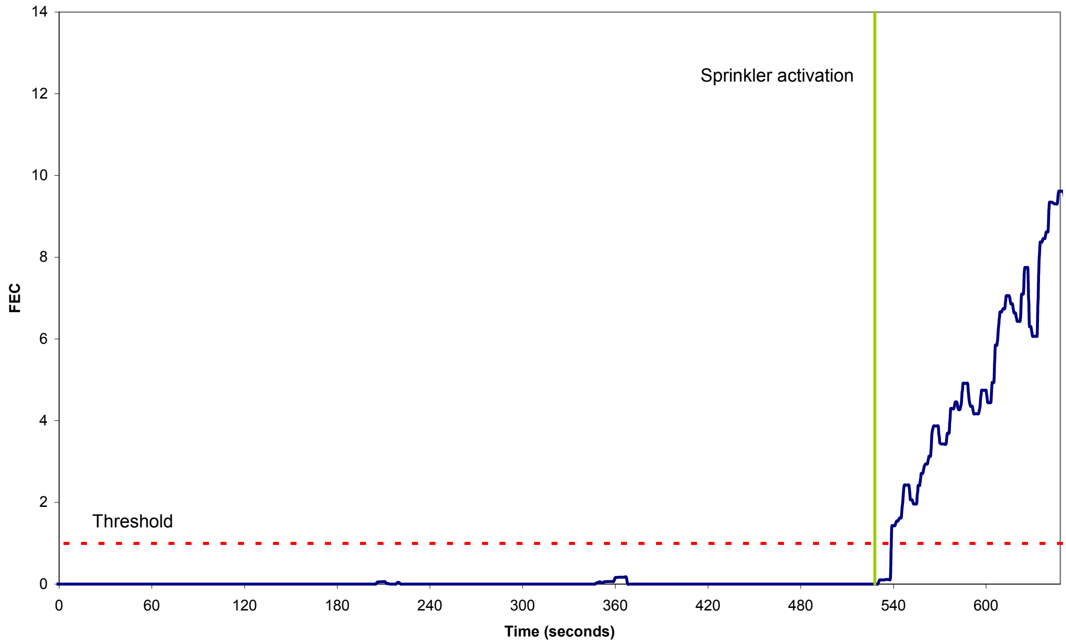


Figure 7.4.1: FEC_{smoke} (Test 18 – 800 mm sampling height)

A full set of graphs showing the FEC_{smoke} results for each test is contained in Appendix G. In every case the FEC_{smoke} threshold was exceeded during the test. A typical FEC_{smoke} result is shown above in Figure 7.4.1.

From Figure 7.4.1 it can be seen that the level of obscuration was low for the majority of the fire. This was typical of all the tests since the smoke formed a hot buoyant layer that collected at the ceiling and descended slowly in a fairly uniform manner, thus keeping the lower part of the compartment clear.

Once the sprinkler activated however the FEC_{smoke} rose rapidly, in this example exceeding the threshold in 29 seconds. This is because the sprinkler activation disrupted the thermal layering within the compartment, both cooling and dragging the smoke down into the lower part of the compartment. Of the tests where visual obscuration measurements were made, 9 involved sprinkler activation. In 5 of these 9 tests the FEC_{smoke} threshold was exceeded following sprinkler activation. The delay time ranged from 3 seconds to 29 seconds.

If an occupant were reliant on sprinkler activation to provide warning of fire in these fire scenarios, they would be confronted with extremely limited visibility when attempting to escape through the living room. Figure 7.4.2 contains a sequence of frames taken from the video of footage of a test showing the disruption of the thermal layer and subsequent loss of visibility following sprinkler activation.
Of the 4 remaining tests where the threshold was exceeded prior to sprinkler activation, two had sampling heights of 1600 mm. This meant that the descending smoke layer reached the measuring devices earlier. Given that the FEC_{smoke} threshold only exceeded sprinkler activation by 55 seconds and 86 seconds in these tests, it is unlikely that visibility at the 800 mm height would have been compromised prior to sprinkler activation.

The two tests measured at 800 mm where the FEC_{smoke} threshold was exceeded prior to sprinkler activation (Tests 11 and 13) were fairly slow fires, as indicated by their sprinkler activation times of 1112 and 794 seconds respectively. This allowed the smoke layer to descend well into the lower part of the room before sufficient heat developed at ceiling level to activate the sprinkler system.

30 secs before sprinkler activation

1 sec before sprinkler activation

5 secs after sprinkler activation

10 secs after sprinkler activation

15 secs after sprinkler activation

20 secs after sprinkler activation

Figure 7.4.2: Visual obscuration following sprinkler activation (Test 3)

In the final 3 tests sprinkler activation did not occur. If an occupant were reliant on sprinkler activation as a means of warning in these scenarios, then the smoke layer would descend below 800 mm without them even being aware of the presence of a fire. As an example of this scenario, the FEC_{smoke} results for Test 20 are shown inFigure 7.4.3. A summary of the FEC_{smoke} threshold versus sprinkler activation time for each test is provided in Table 7.4.1.

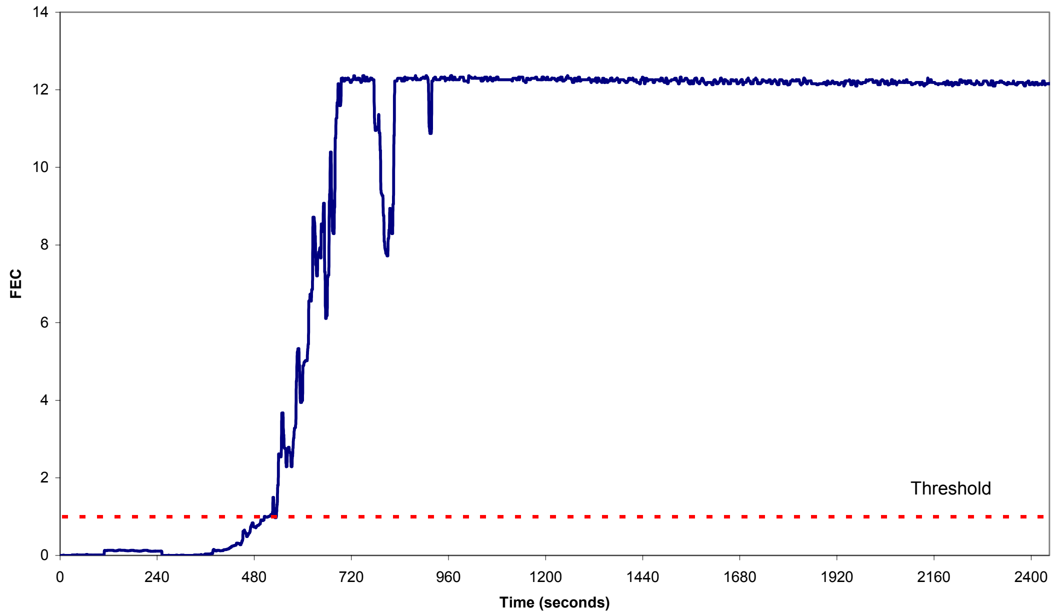


Figure 7.4.3: FEC$_{smoke}$ (Test 20 – 800 mm sampling height)

The tests indicate that sprinkler activation has a significant impact on visual obscuration within the apartment under this type of fire scenario. This in itself is cause for concern when proposing to rely on sprinkler activation as the fire detection system. The situation is not improved by the fact that in the tests where the sprinkler did not appear to have an effect on visibility, the FEC$_{smoke}$ threshold was still exceeded. It should be noted however that the sprinkler system was only run for a maximum period of 2 minutes in any of the tests. It is not known what affect the sprinkler discharge would have had on the visual obscuration in the compartment after this time. Nevertheless it is reasonable to assume that had the sprinkler activation been the alerting mechanism, the 2 minutes following activation would cover the time during which an occupant would most likely be attempting to escape.

When considering the visibility at different sampling heights in determining egress time, cognisance should be taken of the realistic movement speed at that height, regardless of smoke conditions. For example, good visibility at 1600 mm will allow an occupant to travel at normal walking speed, however if the occupant is required to crouch, or crawl, to remain under the smoke layer, i.e. at the 800 mm sampling height, then their movement speed will be significantly slower.

Table 7.4.1: FEC_{smoke} threshold versus sprinkler activation time

Test	Height (mm)	Sprinkler (secs)	FEC_{smoke} (secs)	Difference (secs)	First event
9	800	477	487	10	Sprinkler
10	800	434	463	29	Sprinkler
11	800	1112	611	501	FEC_{smoke}
12	800	217	220	3	Sprinkler
13	800	794	645	149	FEC_{smoke}
14	1600	569	483	86	FEC_{smoke}
15	1600	DNA	442	N/A	N/A
16	1600	518	463	55	FEC_{smoke}
17	800	DNA	330	N/A	N/A
18	800	528	539	11	Sprinkler
19	800	-	-	-	-
20	800	DNA	505	N/A	N/A
21	800	427	446	19	Sprinkler

DNA : Did Not Activate - : No measurements taken due to TV failing to ignite

7.5. Temperature

In a sprinkler controlled fire scenario, temperature is not likely to be a significant factor in determining tenability within the compartment. Nevertheless it was still considered pertinent to examine the temperature profiles during each test. Graphs showing the thermocouples temperatures for every test are included in Appendix H. A typical time temperature graph is show below in Figure 7.5.1.

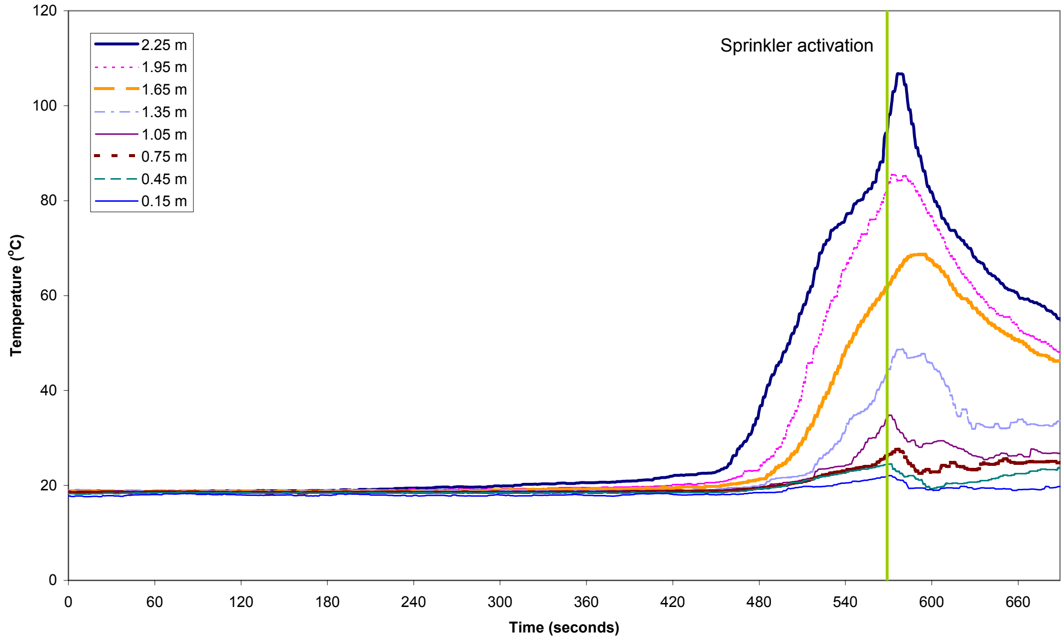


Figure 7.5.1: Time temperature curve (Test 14)

The graph shows a clear rise in temperature until a short time after sprinkler operation, at which point the temperature drops away steadily. The temperatures in the upper sections of the compartment experience the sharpest rise, and reach the greatest values. This is to be expected due to the thermal layering that occurs in the compartment, with the hot buoyant smoke hot concentrated in the upper part of the compartment.

The graph shows that the maximum gas temperature 150 mm below the ceiling (106°C) exceeds the nominal sprinkler activation temperature of 68°C. There are a number of reasons for this, including the much smaller RTI of the thermocouple wire and conduction from the sprinkler bulb to the metal housing and water pipe. Another factor could be conduction through the uninsulated ceiling of the compartment, resulting in lower temperatures in the boundary layer (where the sprinkler head is located) than at the thermocouple 150 mm below the ceiling.

While the maximum temperature never approached the 200°C suggested by Purser as a hot upper layer tenability threshold, the tests do indicate that caution must be employed when equating sprinkler activation times to gas temperatures. It should be noted that the thermocouple tree is located in the centre of the room, and so the activated sprinkler head is approximately 2 metres closer to the fire, and therefore should be exposed to higher temperatures. In this particular example the top thermocouple reached 68°C 47 seconds before the sprinkler operated. The gas temperature 750 mm off the floor (approximate assumed escape height) never exceeded 30°C throughout the test.

Table 7.5.1 contains a summary of maximum gas temperatures at selected thermocouple heights for each test. This table also contains the top thermocouple temperature at sprinkler activation time, plus the time delay between the top thermocouple reaching 68°C and the sprinkler activating.

In many of the tests, maximum temperatures were recorded following sprinkler activation due to time lags. While the post sprinkler activation temperatures appear realistic, some degree of caution is required given that water from the sprinkler discharge was impinging directly on the thermocouples.

The maximum temperatures at 750 mm above floor level ranged from 26°C to 65°C, with an average maximum temperature of 39°C. These temperatures would not be considered life threatening to an occupant attempting to evacuate the apartment. At 1650 mm above floor level, the maximum temperatures recorded over the 21 tests ranged from 52°C to 84°C. The average maximum at this height was 69°C.

The higher end of these temperatures might cause injury depending on the moisture saturation level in the compartment. It is also possible that the higher end temperatures may cause occupants to hesitate to enter the fire compartment.
If an occupant is alerted by an emergency warning device and is subsequently confronted with smoke and elevated temperatures in the living room (even if they are not life threatening at the lower levels), they may be reluctant to enter that space, fearing the fire they naturally associate with the heat and smoke. This would be particularly relevant once the FEC_{smoke} threshold has been exceeded, and they are not able to directly assess the size of the fire, and hence the degree of threat it represents.

The maximum temperatures recorded at the top thermocouple (2.25 metres above floor level) ranged from 82°C to 152°C. It should be noted that the value of 152°C obtained from Test 3 was significantly higher than any other test. Test 3 was the only test in which both sprinkler heads activated. The next highest maximum was 114°C. The average maximum temperature was exactly 100°C. At this height an occupant is unlikely to come into direct contact with the gases, and none of these temperatures exceeds Purser's 200°C threshold for radiated heat from a hot smoke layer.

The temperature recorded at the top thermocouple at the time of sprinkler activation ranged from 73°C to 107°C, with an average temperature of 94°C. The time delay between the top thermocouple reaching 68°C and the sprinkler activating ranged from 5 seconds to 656 seconds. The average delay was 83 seconds.

It should be noted that the time delay of 656 seconds recorded during Test 7 was exceptional, though genuine. However if this outlying value is ignored, the delay ranges between 5 and 151 seconds, with an average time of 42 seconds. In no test did sprinkler activation occur before the top thermocouple reached 68°C.

Table 7.5.1: Temperature and sprinkler activation time comparisons

	Maximum temperatures (°C)			Sprinkler Activation (°C)	Top TC Reached 68°C	Sprinkler Activation	Delay
Test	**0.75 m**	**1.65 m**	**2.25 m**	**2.25 m**	**(Sec)**	**(Sec)**	**(Sec)**
1	52	72	107	107	899	995	96
2	54	74	114	106	3164	3315	151
3	30	83	152	103	395	437	42
4	27	68	108	99	238	261	23
5	50	69	86	DNA	975	DNA	N/A
6	42	70	105	99	747	798	51
7	51	70	92	88	677	1333	656
8	47	66	93	DNA	911	DNA	N/A
9	30	68	104	86	469	477	8
10	30	58	83	73	429	434	5
11	41	63	95	93	1066	1112	46
12	28	67	104	95	197	217	20
13	42	69	103	94	768	794	26
14	27	69	106	94	522	569	47
15	65	84	92	DNA	545	DNA	N/A
16	26	62	107	94	504	578	14
17	62	79	87	DNA	859	DNA	N/A
18	27	65	99	99	492	528	36
19	-	-	-	-	-	-	-
20	46	63	82	DNA	1008	DNA	N/A
21	26	52	83	82	401	427	26

DNA : Did Not Activate - : No measurements taken due to TV failing to ignite

7.6. Heat Release Rate

The heat release rate (HRR) was calculated using the mass loss rate of the burning TV set (see Equation 4.4.1). Mass loss curves for all but two of the tests are contained in Appendix K. The effective heat of combustion Δh_c was assumed to be 30 MJ/kg. This figure was taken from Babrauskas [19], and was based on the assumption that in all cases where ignition occurred, the television set casing must be non-fire retarded (i.e. HB rated). It should be recognised that while most TV casings would be made from high impact polystyrene [16,19,25], the effective heat of combustion might in reality vary from one set to the next. Therefore the assumption of 30 MJ/kg as the effective heat of combustion may not necessarily accurately portray the burning characteristics of each television set tested. It should also be noted that the mass loss information recorded during the tests required some manipulation in order to be usable (see Section 6.4), which in turn may have introduced an element of uncertainty into the data. For these reasons the HRR results contained in this report should be treated with some caution.

Mass loss measurements allowed the HRR to be calculated for 18 of the 20 tests in which ignition was successful. In the other two tests the outputs did not provide a clear mass loss curve, and therefore HRR calculations could not be obtained. Graphs showing the heat release rates for each test are contained in Appendix I, and a representative graph is shown below in Figure 7.6.1. The peak heat release rate ranged from 55 kW to 195 kW, with an average peak HRR of 133 kW. Table 7.6.1 shows a summary of the peak heat release rates for each test. It is interesting to note that for the three identical pairs of sets the variation in peak HRR is not substantial (3 kW for two pairs, and 31 kW for the third). This gives some confidence in the use of the mass loss technique, however it does not provide any more certainty regarding the chosen effective heat of combustion.

Due to the fact that sprinkler discharge spray hitting the weighing assembly affected the mass loss measurements, the HRR curves are only provided up until the point of sprinkler activation. On some occasions the results appear to be affected prior to the indicated activation time. This is most likely caused by the averaging process used on the raw mass loss data. In the tests where the sprinkler did not activate HRR data is shown for as long as possible, however given the output rate of 13.84 weigh values per second, limitations on the amount of data Excel is capable of displaying in a graph meant that the HRR information is frequently not included for the entire duration of a test.

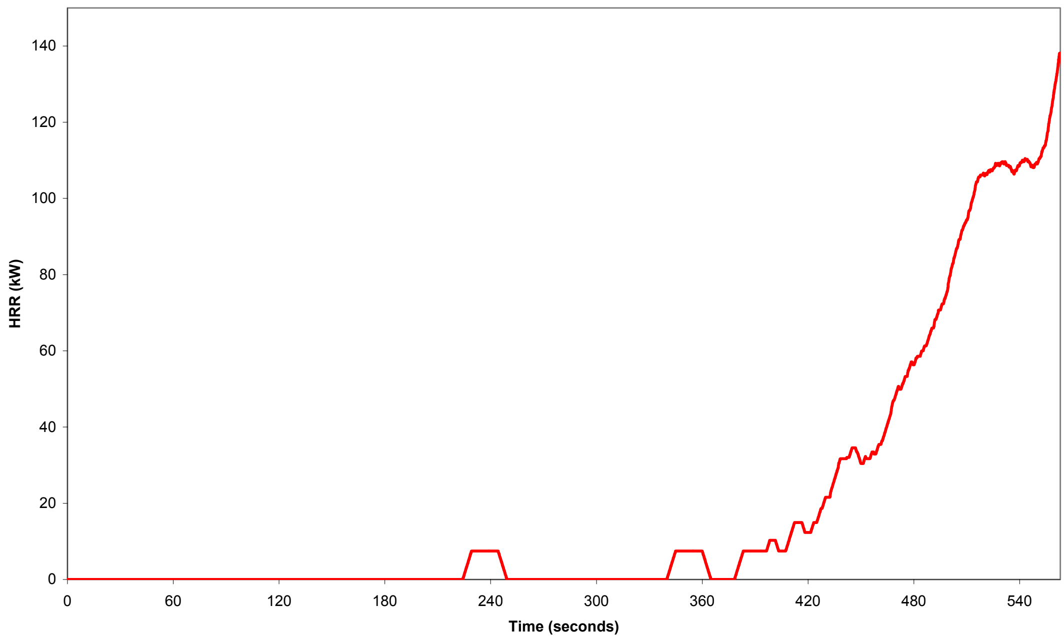


Figure 7.6.1: Heat release rate curve (Test 14)

It is worth noting that in the tests where the sprinkler did not activate, the peak HRR tended towards the lower end of the range (between 73 kW and 120 kW). In only one of these cases (Test 20) did the peak HRR exceed 100 kW. Test 20 is also one of the two identical sets which had the greatest variance in peak HRR. The HRR curve for Test 20 is contained in Figure 7.6.2 and from this it can be seen that the peak occurs at a sharp spike. This may be a function of the mass loss processing method, and if further smoothing were to occur, the peak would likely occur at around 100 kW. 100 kW is the type of value that would satisfy both the HRR comparison with the same model set (Test 8), and the non-activation of the sprinkler. It should also be noted however that the sprinkler did activate in tests with lower peak HRRs, i.e. 55 kW and 78 kW. These results may in turn indicate that the effective heat of combustion used is not appropriate for all the televisions tested.

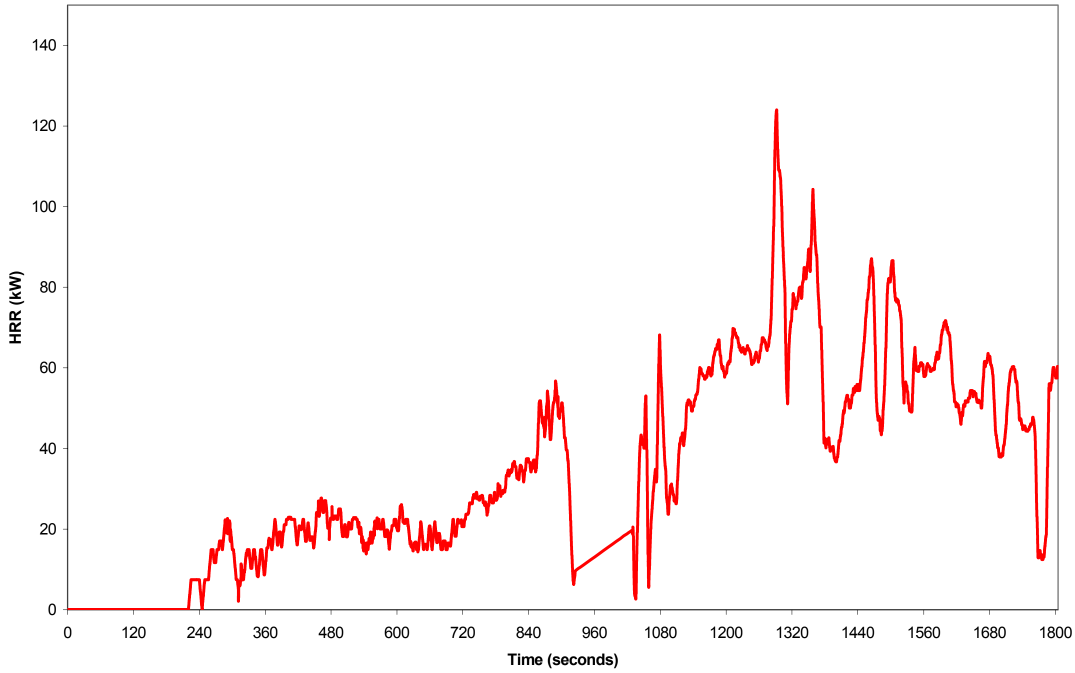


Figure 7.6.2: Heat release rate curve (Test 20)

The peak heat release rates recorded in these tests are markedly lower than those contained in the literature review for non-fire retarded sets (see Section 2.3), which were typically in the range of 230 - 250 kW, and as high as 570 kW. While this could be a result of the methodology (including the possibility of pieces of TV continuing to burn after falling off the weighing assembly), it could also be explained by the fact that fire growth was limited by sprinkler activation. It should be noted that in Test 3 the ceiling gas temperature was sufficiently high to activate both sprinklers in the compartment. It would be expected that this test would have an exceptionally high HRR as well, however the peak HRR was only 138 kW, which was just above the average for the tests. This appears to reinforce the fact that selecting an accurate heat of combustion is critical.

Table 7.6.1: Comparison of peak heat release rates

Test	Peak HRR (kW)	Sprinkler Activation	Comments
1	190	Yes	
2	?	Yes	Error in mass loss data
3	138	Yes	Both sprinklers operated
4	174	Yes	Same set as Test 16
5	88	No	
6	170	Yes	
7	?	Yes	Error in mass loss data
8	89	No	Same set as Test 20
9	191	Yes	
10	139	Yes	
11	78	Yes	
12	195	Yes	
13	55	Yes	
14	138	Yes	Same set as Test 18
15	96	No	
16	171	Yes	Same set as Test 4
17	73	No	
18	135	Yes	Same set as Test 14
19	-	-	No ignition
20	120	No	Same set as Test 8
21	150	Yes	

? : Error in mass loss data - : No measurements taken due to TV failing to ignite

7.7. Fractional Effective Dose (Asphyxiant)

7.7.1. FED Results over Duration of Test

The fractional effective dose of asphyxiant gases was calculated using the method described by Purser (see Equation 4.1.2). Graphs representing the cumulative FED over the duration of each test are contained in Appendix J. A typical graph is provided below in Figure 7.7.1 showing the incapacitation threshold of 0.1, along with the sprinkler activation time.

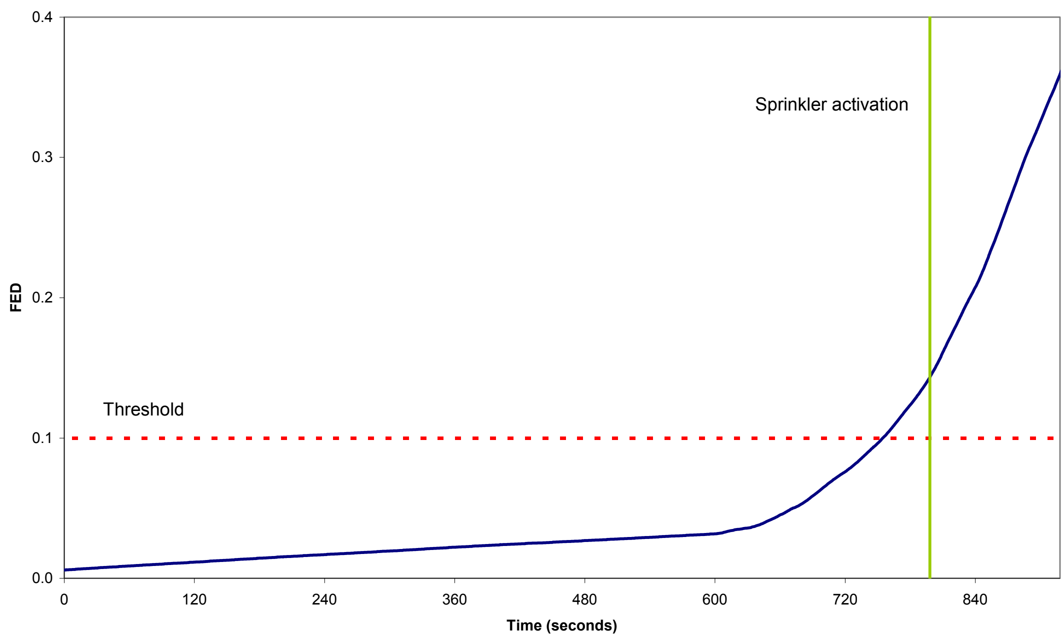


Figure 7.7.1: FED Asphyxiants (Test 6)

The FED results for all the tests are summarised in Table 7.7.1. It is important to note that the sampling height for Tests 14 - 16 was 1600 mm above floor level. This sampling height is a lot closer to ceiling level and therefore to the hot gas layer containing the majority of the toxic combustion products. It would be expected that exposure to higher concentrations of asphyxiant gases would occur at this level, and that exposure would occur earlier in the test.

The FED values attained in each test varied considerably with the maximum FED ranging from 0.0024 to 4.56. Of the 20 tests in which ignition occurred, the FED threshold was exceeded in 13 cases prior to the end of the test.

In tests where sprinkler activation occurred, the end of the test was taken as the time at which the sprinkler was shut off. However in one further test (Test 12) the FED was exceeded only 22 seconds after the sprinkler was shut off. Shutting off the sprinkler would definitely have had an affect on conditions within the compartment, and therefore possibly affected the FED calculations as well. However the results for this test (see Figure 7.7.2) show that the FED values after sprinkler shut off are a continuation of a clear trend line established well before the sprinkler was shut off. For this reason this test is also included in the analysis.

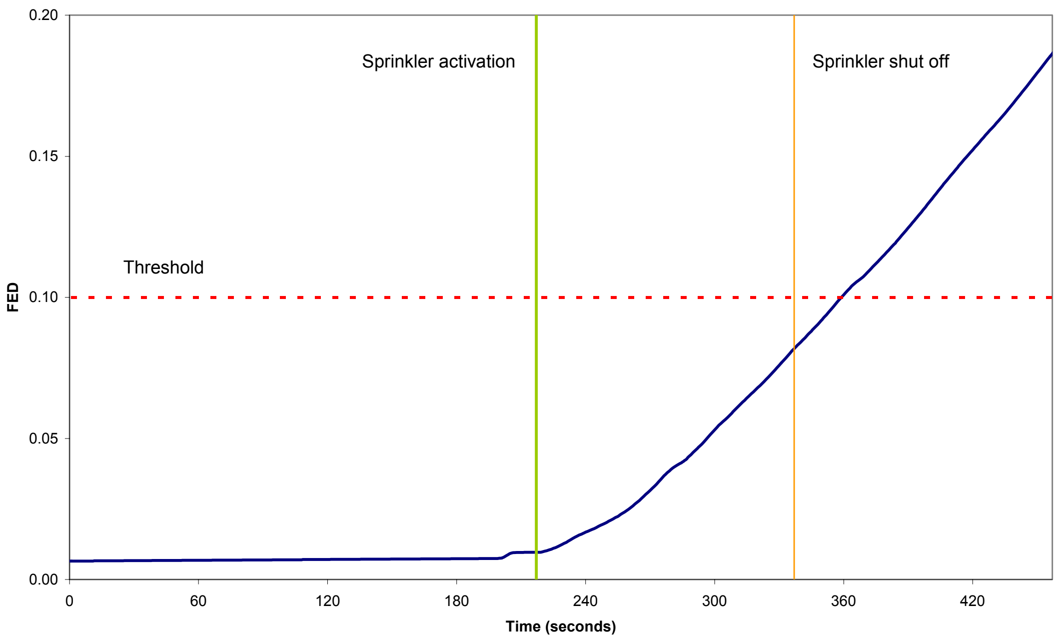


Figure 7.7.2: FED Asphyxiants (Test 12)

In the 14 tests where the FED limit was exceeded, the time to reach the threshold ranged from 359 seconds to 2255 seconds (37 min 35 sec).

Of these 14 tests, sprinkler activation occurred 9 times. In 4 tests the FED threshold was exceeded prior to sprinkler activation. Surprisingly, this did not include any of the tests sampled at 1600 mm. The difference between reaching the FED threshold and sprinkler activation ranged from 43 seconds to 1060 seconds (17 min 40 sec).

In the 5 tests where the sprinkler activated before the FED threshold was exceeded, the difference was much less. In these tests the difference ranged between 43 seconds and 142 seconds. This means that had sprinkler activation been relied on to warn the occupants of fire, the available escape time following sprinkler activation would have been limited. It is likely that sprinkler activation contributed to reduced tenability at the sampling height by disrupting the thermal layer, causing a greater concentration of toxic products to enter the lower portion of the compartment. It should be noted that this group included two tests sampled at 1600 mm. In all 5 tests where the sprinkler did not activate (including one sampled at 1600 mm), the FED threshold was exceeded.

It should be noted that the FED graphs do not always commence at zero. This is probably due to residual elevated levels of CO and CO_2, and/or lowered O_2 levels from proceeding tests. The compartment was aired at the end of each test using a positive pressure ventilation fan, however this may not always have returned the compartment to ambient conditions. These initial FED readings were so far below the threshold of 0.1 that their effect would have been negligible by the time the FED threshold was actually exceeded, and therefore no attempt has been made to adjust the values.

7.7.2. Comparison of Sampling Heights

In two of the tests in which gas was sampled at 1600 mm (Tests 14 and 16), the television sets were the same model as those used in tests sampling at 800 mm. This provided an opportunity to examine the effect of varying the sampling height on the FED results. Test 14 used the same model of Transonic television as Test 18, and Test 16 used the same Philips model as Test 4.

There are a number of similarities between Tests 14 and 18 that make the comparison worthwhile. Both sets were ignited using the same method (Method 1), and sprinkler activation times were only 41 seconds apart (at 569 and 528 seconds respectively). Normalised mass loss curves for each test are provided in Figure 7.7.3 and give an indication of the fire growth characteristics of the two tests. The mass loss curves have been normalised because although these are the same model televisions, the initial mass differed by approximately 0.5 kg. This is possibly due to internal componentry that had been removed during servicing, and not replaced when it was apparent that the set could not be repaired. It is unlikely that this would have a significant effect on the burning characteristics of the set. Despite absolute differences in mass, the mass loss during the fire follows a similar pattern in both tests, indicating that fire development characteristics would have been fairly similar.

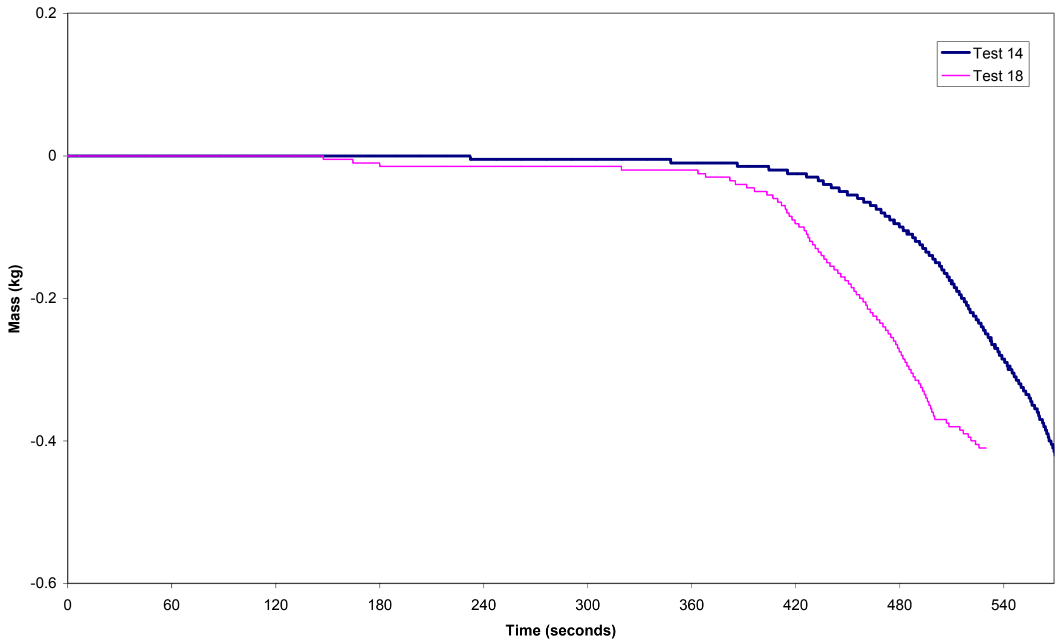


Figure 7.7.3: Normalised mass loss curves for same model television set (Tests 14 and 18)

Figure 7.7.4 shows the comparative FED values for the two tests. At a sampling height of 1600 mm, the FED threshold is exceeded in 684 seconds, which is 115 seconds after sprinkler activation. At a sampling height of 800 mm, the FED was not exceeded, even after sprinkler activation. Examination of the graph for Test 14 (1600 mm sampling height) reveals that the FED was only just exceeded. It is possible that there were not sufficient levels of toxic products in the compartment to achieve the threshold even once the smoke layer was dispersed into the lower level following sprinkler activation.

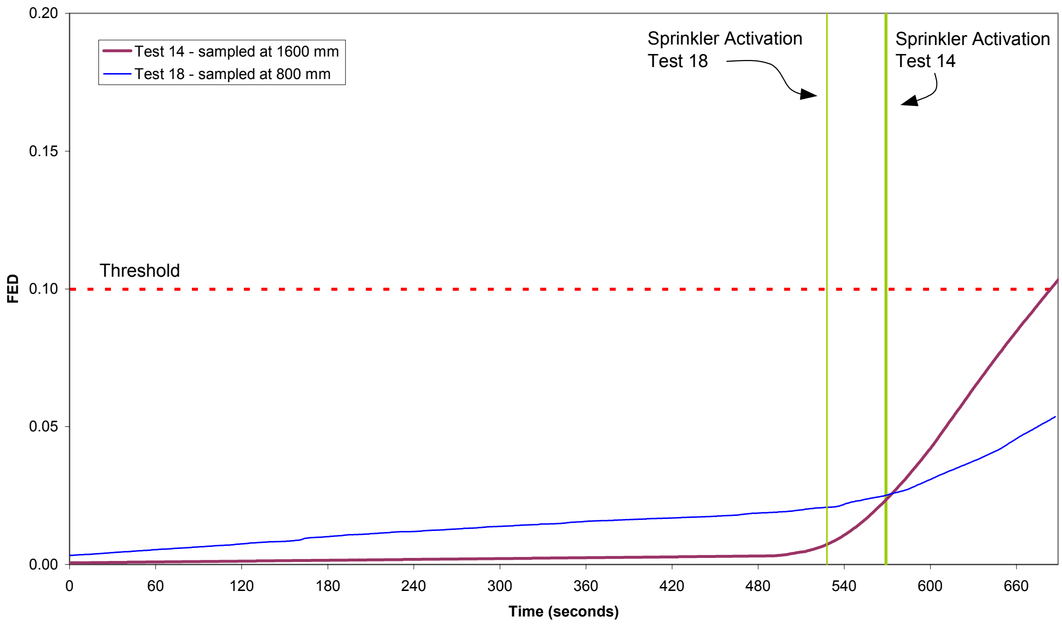


Figure 7.7.4: FED for same model television sets sampled at different heights (Tests 14 and 18)

Comparing Tests 4 and 16 was not as easy since similarities between the two tests were not so apparent. The sprinkler activation time for Test 4 was 261 seconds, whereas the sprinkler activation time for Test 16 was 518 seconds (a difference of 257 seconds). This result was likely to have been influenced by the fact that Test 4 required double wicking to the rear of the set to achieve ignition (i.e. Method 2), which may have resulted in faster fire development leading to earlier sprinkler activation. This in itself is interesting in that it seems to indicate either the ignition properties of the casing materials vary from batch to batch, or that the uncertainty in achieving sustained combustion extends beyond the timeframe allowed for the ignition method. The mass loss curves for the two tests are shown in Figure 7.7.5.

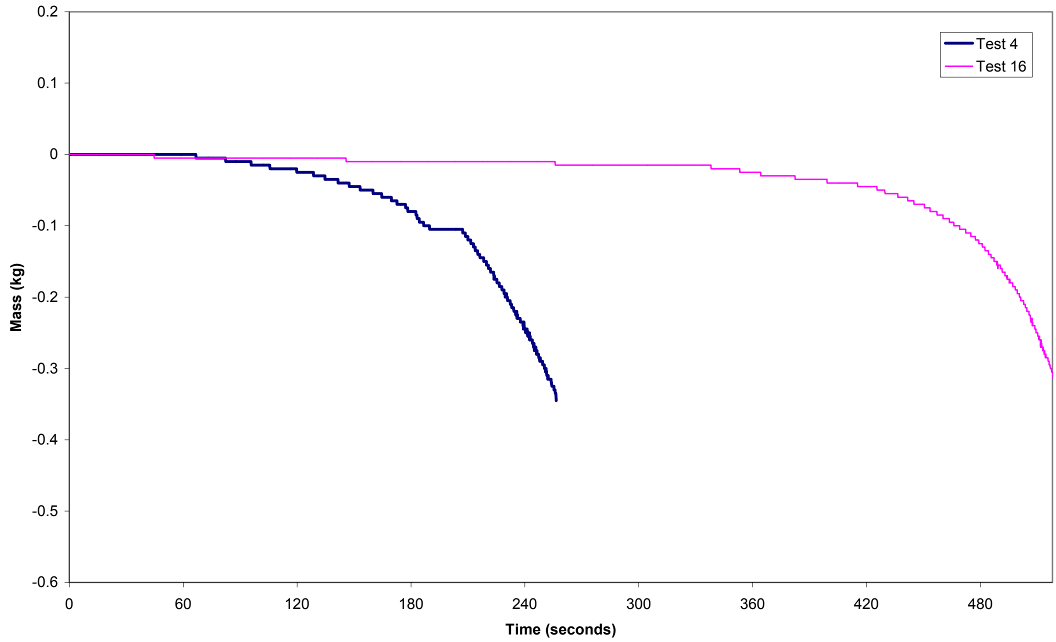


Figure 7.7.5: Normalised mass loss curves for same model television sets (Tests 4 and 16)

As with the previous comparison it should be noted that the initial mass differed, this time by a relatively substantial 1.6 kg, although possibly for the same reason as last time. Once again however the mass loss of the two sets during the fire is similar, although mass loss occurs significantly later in Test 16. This is in keeping with the later sprinkler activation time recorded in Test 16.

Figure 7.7.6 shows the comparative FED values for the two tests. Once again the threshold is exceeded at the 1600 mm sample height (Test 16), on this occasion in 585 seconds, which was 67 seconds after sprinkler activation.

A maximum FED of 0.13 was achieved during this test. The same model television sampled at 800 mm did not exceed the threshold, with the FED measurement reaching only 0.0073. This is likely to be due to the fact that the fire was faster and so both the concentration of toxins, and the available exposure time, was reduced.

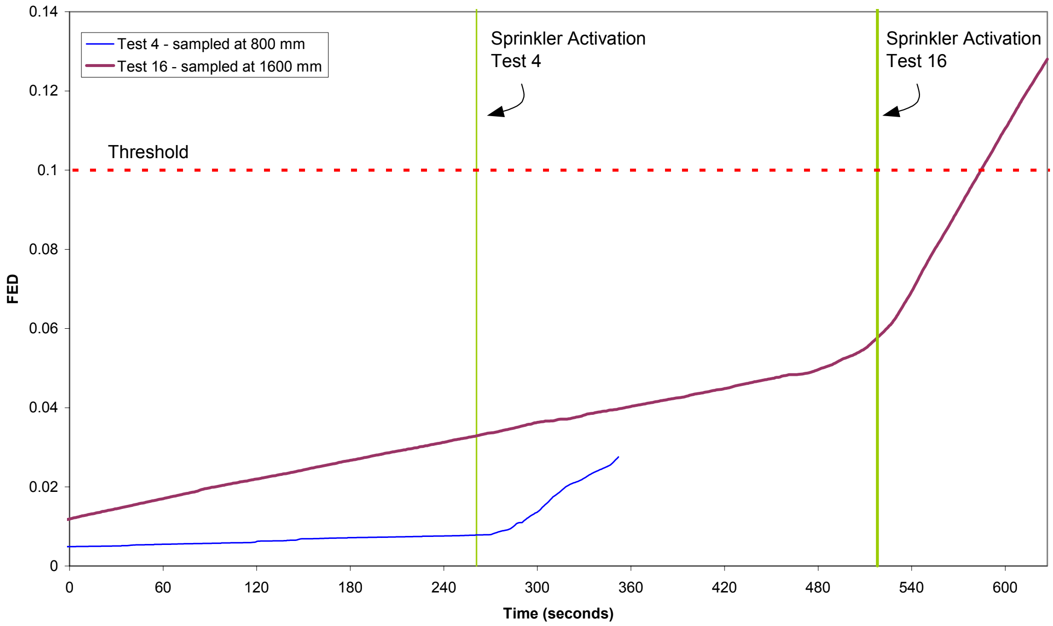


Figure 7.7.6: FED for same model television sets sampled at different heights (Tests 4 and 16)

Examination of only two pairs of tests is insufficient to draw any firm conclusions, and the variability in the burning characteristics inherent in the television sets contributes to the uncertainty, however the results discussed reinforce the obvious assumption that tenability conditions will be better at a lower height within the compartment. Put another way, sampling height does have an affect on the tenability limits imposed by FED analysis. Therefore selecting a sampling height that realistically simulates the behaviour of an occupant attempting to escape through the room of fire origin is important in assessing whether evacuation is achieved safely.

Table 7.7.1: FED Results Summary

Test	Maximum FED	0.1 FED Exceeded (Sec)	Sprinkler Activation (Sec)	Difference (Sec)	First Event
1	0.102	1055	995	60	Sprinkler
2	0.97	2255	3315	1060	0.1 FED
3	0.0024	N/E	437	N/A	N/A
4	0.0073	N/E	261	N/A	N/A
5	3.01	1031	DNA	N/A	N/A
6	0.39	755	798	43	0.1 FED
7	1.83	779	1333	554	0.1 FED
8	4.56	724	DNA	N/A	N/A
9	0.014	N/E	477	N/A	N/A
10	0.054	N/E	434	N/A	N/A
11	0.19	1064	1112	48	0.1 FED
12	0.082	359*	217	142	Sprinkler
13	0.16	837	794	43	Sprinkler
14	0.103	684	569	115	Sprinkler
15	1.30	693	DNA	N/A	N/A
16	0.13	585	518	67	Sprinkler
17	0.94	638	DNA	N/A	N/A
18	0.042	N/E	528	N/A	N/A
19	-	-	-	-	-
20	1.82	912	DNA	N/A	N/A
21	0.016	N/E	427	N/A	N/A

* FED threshold exceeded 22 seconds after sprinkler shut off

DNA : Did Not Activate N/E : FED not exceeded N/A : Not applicable - : No measurements taken

7.7.3. Grab Sample Results for HCN and HCl

Grab samples were taken at random intervals during the tests to identify the presence of these two toxicants, and to examine the impact they might have on the FED. Because continuous sampling equipment was not available, it had already been decided to discount these two gases from the final FED calculation. This meant that the FED results obtained from the tests could be viewed as a 'best case', in that the presence of the asphyxiant HCN, or the irritant HCl, would adversely affect the tenability results. The grab samples were intended to provide a qualitative assessment of the likely contribution these gases might have played in the overall toxicity hazard.

As it eventuated, the presence of neither gas was measured during any of the random sampling. This may mean that they were not it the compartment atmosphere in sufficient concentrations to register on the measuring equipment, or it may mean that the sampling technique was not appropriate for the task. It should be noted however that previous studies of TV fires did not reveal the presence of HCN or HCl in measurable quantities either [19,25]. The results of the grab sampling carried out during the tests are summarised in Table 7.7.2 below.

Table 7.7.2: HCN and HCl grab sampling results

Test	Height	Time (s)	Gas	Sprinkler	Concentration
5	800 mm	870	HCN	No	< 50 ppm
8	800 mm	945	HCN	No	< 50 ppm
8	800 mm	1155	HCl	No	< 20 ppm
9	800 mm	525	HCl	Yes	<20 ppm
11	800 mm	900	HCl	No	< 20 ppm
12	800 mm	270	HCl	Yes	< 20 ppm
13	800 mm	780	HCl	Yes*	< 20 ppm
15	1600 mm	690	HCl	No	< 20 ppm
15	1600 mm	1380	HCN	No	< 50 ppm
17	800 mm	1200	HCl	No	< 20 ppm
20	800 mm	885	HCN	No	< 50 ppm
20	800 mm	1155	HCl	No	< 20 ppm

* Sprinkler activated during sampling

7.8. Alert Time versus Available Escape Time

The cumulative FED assessed over the entire duration of the fire does not in itself provide useful information for evaluating the ability of an occupant to safely evacuate, since the occupant's exposure time is likely to be significantly shorter. For analysis purposes the scenario assumes that an occupant is in another room (i.e. asleep in the bedroom) with the connecting door shut. The occupant is alerted to the fire by one of the fire safety systems, at which point an attempt is made to evacuate through the room in which the fire has occurred.

Under this scenario, exposure would commence when the occupant opened the door to the living room (i.e. enclosure of fire origin). The time it would take for an occupant to react to the alert (pre-movement time) and open the door is difficult to quantify, and so for this analysis exposure is considered to commence immediately upon activation of the relevant fire safety system. The success of the occupant's escape attempt is dependent on the time available before the FED threshold is exceeded.

The time at which the FED threshold is exceeded is determined by evaluating the cumulative FED over the duration of exposure, from the beginning of the exposure until the end of the exposure period. Thus the FED calculation can be expressed as follows:

$$FED_{cummulative} = \sum_{t_{start}}^{t_{end}} FED_t \qquad (7.8.1)$$

where

t	=	time (seconds)
t_{start}	=	time at which exposure commences
t_{end}	=	time at which exposure ceases

Normally, the tenability analysis is done over the entire duration of the fire, where t_{start} is the start of the fire (i.e. $t_{start} = 0$). However to present the FED results in terms of alert time versus available escape time, the FED threshold had to be found for an exposure that commenced at any given time t. Ideally this should be calculated for each consecutive time step in the fire, i.e. t_{start} = 0, 1, 2, 3, . . . , end. This would be a very intensive procedure, so to simplify the process, a series of cumulative FED calculations were made with exposure times commencing in 30 second intervals, i.e. t_{start} = 0, 30, 60, 90, . . . , end.

The next step involved finding the time at which the FED threshold was exceeded ($t_{threshold}$) in each consecutive cumulative FED calculation. This allowed the available escape time to be determined by subtracting the time at which the FED threshold was exceeded from the time at which exposure commenced. Therefore the available escape time for each consecutive cumulative FED calculation could be expressed as:

$$\text{Available escape time} = t_{threshold} - t_{start} \qquad (7.8.2)$$

This process resulted in a series of available escape times for each test, where each available escape time corresponded to a particular exposure start time. If the time at which exposure commenced (t_{start}) is considered the alert time, then graphing t_{start} against the corresponding available escape time generates an alert time versus available escape time graph for that particular test.

The activation times of the various fire safety systems in each test is contained in Section 7.3. If the activation time of each fire safety system is considered an alert time, then this information can be overlaid on the alert time versus available escape time graph to give an available escape time for each fire safety system in a particular test. This information is presented in the following section for the 14 tests in which the FED (asphyxiants) was exceeded. One advantage of presenting the FED information in terms of alert time versus escape time is that analysis is not restricted to just the test data. The graphs allow the available escape time for any given alert time to be investigated in each test. Conversely, if a required escape time is known, then the alert time threshold can be determined.

Inspection of the graphs reveals that as the fire develops, the time available for escape reduces. This means that the longer it takes for the occupant to become aware of the fire, the less chance they have of being able to escape safely. The graphs also show that delays in activation time become more critical towards the latter stages of the fire. For example in Test 2, the delay between the operation of the ionisation detector and optical detector in the compartment is 19 seconds, and the corresponding reduction in available escape time is also 19 seconds. In this case the relationship between changes in the alert time and available escape time is linear and the ratio is 1 to 1. However the delay in response time between the ionisation detector and the sprinkler system is 2895 seconds, whereas the difference in available escape times is 1832 seconds. The ratio of available escape time to alert time has dropped to approximately 1 in 3. This pattern can be observed in the majority of the tests where the tenability threshold is exceeded. As the accumulation of toxic products in the compartment becomes more pronounced, every second of delay in alerting the occupant reduces the available time by significantly more than that second. The rate at which this occurs increases as the fire progresses.

A summary of alert time versus available escape time results for each test is also contained in Table 7.8.1 and Table 7.8.2. By subtracting one value from another, the difference in available escape time afforded by each fire safety system can be determined. This information however is better represented on the alert time versus escape time graphs for each test contained in the following section. This section provides an overview of the alert time versus escape time analysis and highlights interesting points as they occur, i.e. the relationship with smoke obscuration and HRR. It should be noted that t_{end} does not represent at definitive point in the fire. Previously, analysis has been stopped when the sprinkler system was shut off. This recognised that shutting off the sprinkler would affect the tenability conditions within the compartment. However as t_{start} approached the sprinkler shut off time, the FED threshold was often not exceeded until after the sprinkler was shut off. This meant that the calculation had to use data captured after the sprinkler was shut off. As inspection of the graphs in the following section reveals no dramatic changes in the alert time versus escape time curve towards the end of the test, use of this data was considered acceptable.

7.8.1. Test 1

The ignition method for this test was Method 3. Sustained combustion took hold after about 11 minutes and the fire grew at a steady rate for approximately 3:30 minutes before developing rapidly until the sprinkler activated some 2 minutes later at an elapsed time of 16:35 minutes.

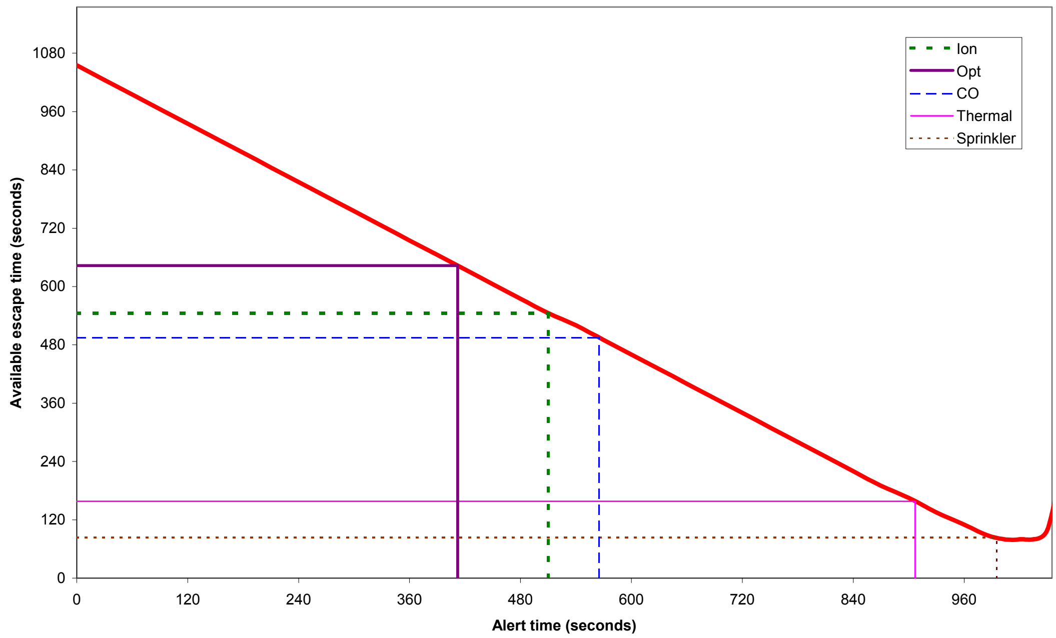


Figure 7.8.1: Alert time versus escape time (Test 1)

7.8.2. Test 2

This set proved difficult to ignite, but successful ignition was eventually achieved using Method 4. Although no heat release rate information is available for this test, the compartment temperature profile indicates that the fire developed slowly for almost 50 minutes, before growing rapidly over the next five minutes prior to sprinkler activation.

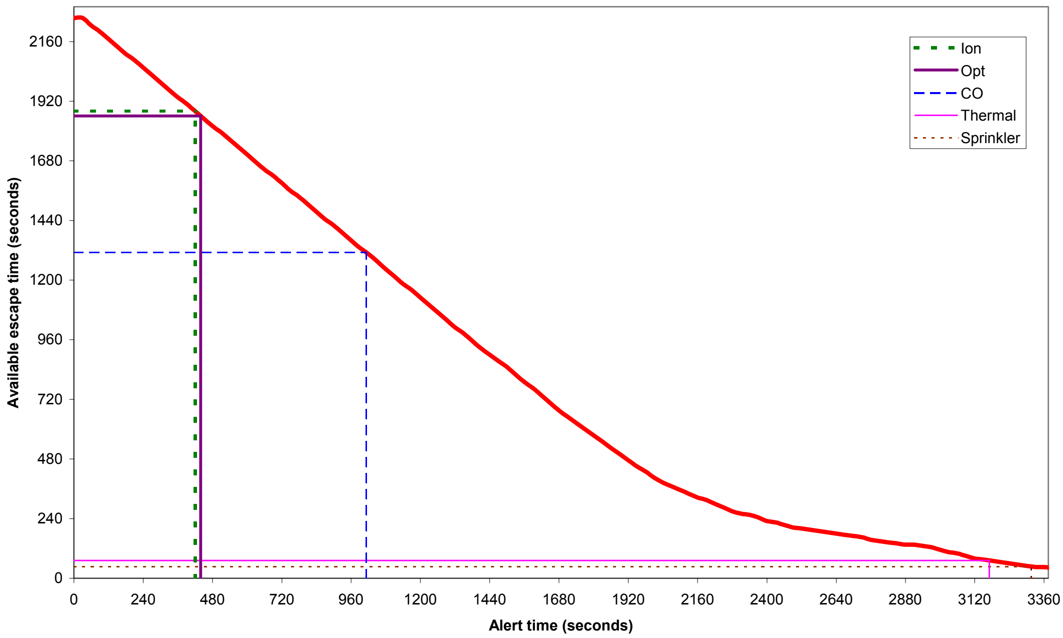


Figure 7.8.2: Alert time versus escape time (Test 2)

It is interesting to note that the CO detector in this test reacted considerably slower than the two smoke detectors, reaching the activation threshold almost 10 minutes later. This variance was far greater than any other experienced in these tests. It may have been a consequence of the slow growing fire, or a problem with the CO detector.

The analogue response of the four detectors used in this test is shown below in Figure 7.3.1. From this graph it can be seen that the CO detector initially responded at a similar time to the two smoke detectors, but levelled off before reaching the activation threshold.

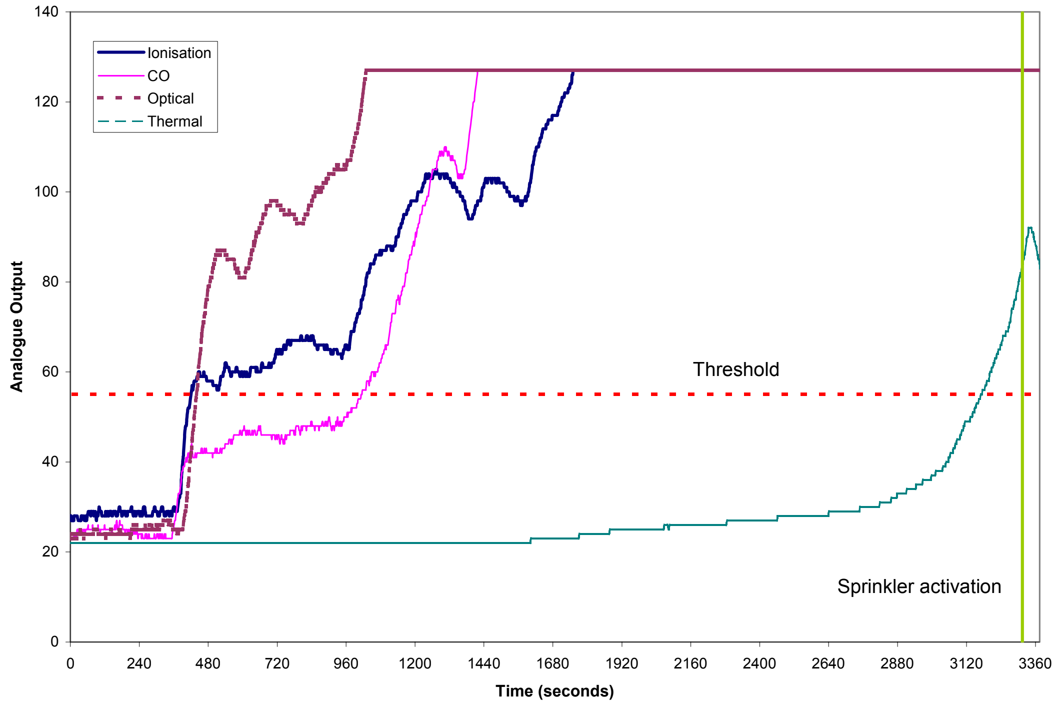


Figure 7.8.3: Fire safety system response (Test 2 - Compartment)

7.8.3. Test 5

Although the television set in this test was easily ignited, the peak heat release was not particularly high (less than 90 kW). Compartment temperatures reached a maximum of only 86°C, which was insufficient to cause sprinkler activation. The fire peaked around 11 minutes after ignition and then steadily declined until the test was terminated after 38 minutes.

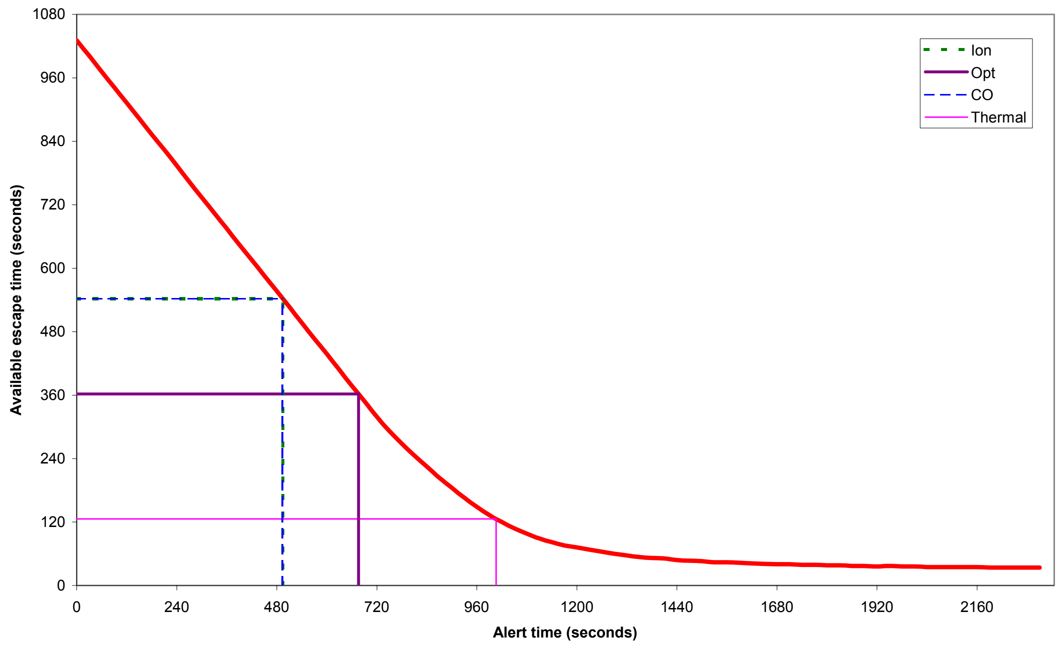


Figure 7.8.4: Alert time versus escape time (Test 5)

7.8.4. Test 6

Ignition in this test was achieved using Method 3. Sustained combustion occurred after 6 minutes, and the fire developed steadily to a HRR of 110 kW at the 11 minute mark, before dying off. Renewed fire development occurred a minute later and the HRR rose steeply to peak at 170 kW at an elapsed time of approximately 13 minutes. This peak was accompanied by the activation of the sprinkler system.

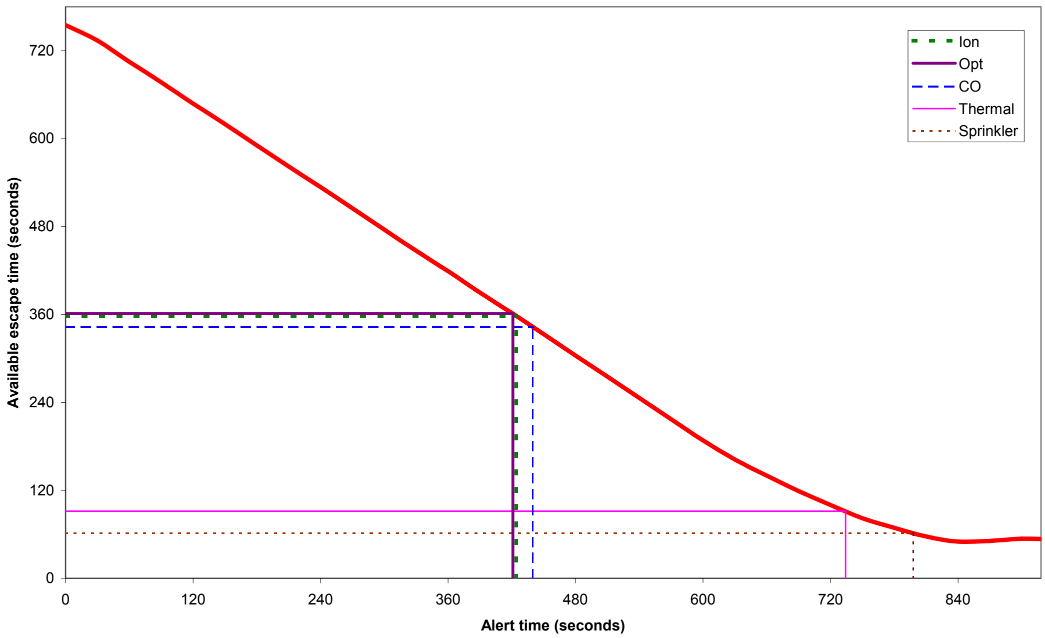


Figure 7.8.5: Alert time versus escape time (Test 6)

7.8.5. Test 7

Method 3 was used in this test to achieve ignition, but it should be noted that Methods 1 and 2 were not attempted because there was no suitable position to locate the candle at the rear of the set. Once again no HRR data is available for this test, but the temperature profile indicates a fire that developed moderately for approximately 13 minutes before levelling off into a fairly steady state fire. Sprinkler activation eventually occurred some 9 minutes after that, at around the 22 minute mark.

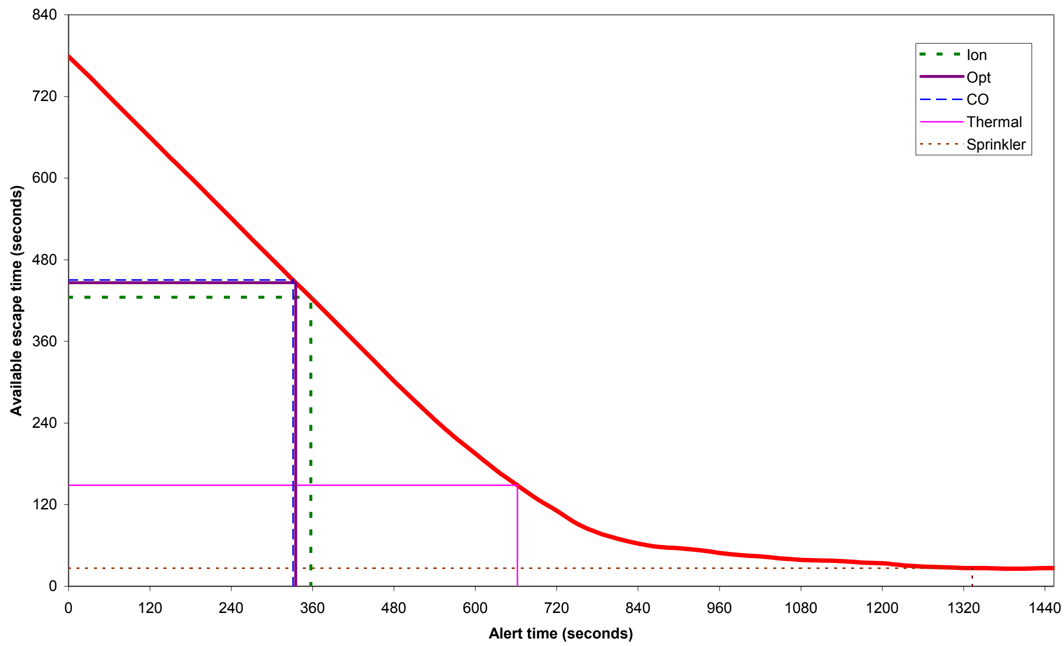


Figure 7.8.6: Alert time versus escape time (Test 7)

7.8.6. Test 8

The set used in this test was difficult to ignite, and Method 4 was required to achieve sustained combustion. The HRR results indicate that sustained combustion occurred after about 10 minutes, and the fire initially developed steadily. However after reaching a peak of less than 90 kW at the 20 minute mark it continued in a fairly steady state phase at a low HRR of between 40 - 50 kW for another 8 minutes. It then climbed to a second peak of 80 kW, after which the fire started to die away. The sprinkler did not activate and the test was stopped after about 36 minutes.

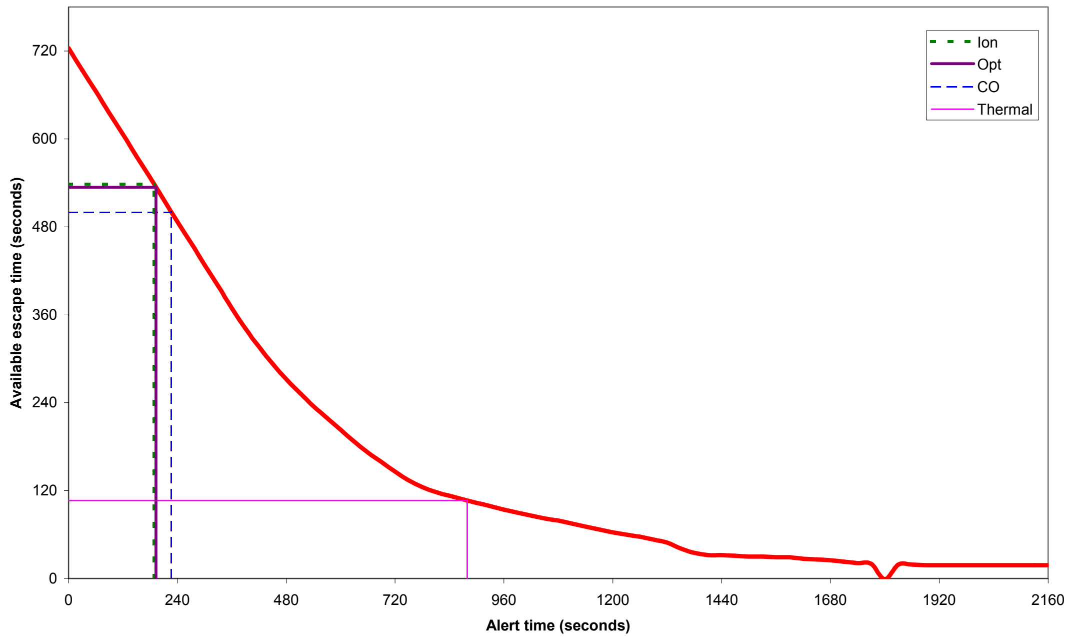


Figure 7.8.7: Alert time versus escape time (Test 8)

7.8.7. Test 11

This fire was ignited using Method 3. After showing some initial strong growth at the 5 minute mark, development was arrested and TV continued to burn steadily at a much slower growth rate. The sprinkler activated about 19 minutes into the fire when the mass loss data indicated that the HRR had reached 75 kW. No information was recorded from the analogue smoke and fire detectors during this test.

Figure 7.8.9 shows the FEC_{smoke} graph for this test. The FEC_{smoke} threshold at 800 mm was exceeded at 611 seconds. By sprinkler activation the reading was over 12 (OD/m = 2.5) indicating near 100 percent obscuration. Therefore the compartment would have been heavily smoke logged when the occupant was attempting to escape. This would increase the amount of time required for the occupant to evacuate the apartment.

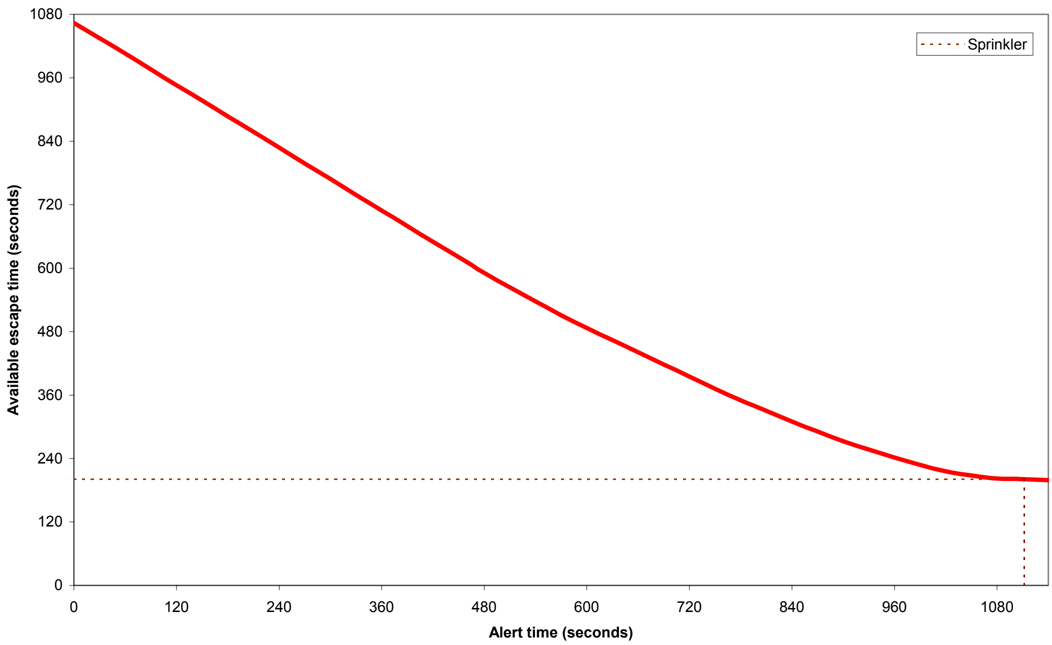


Figure 7.8.8: Alert time versus escape time (Test 11)

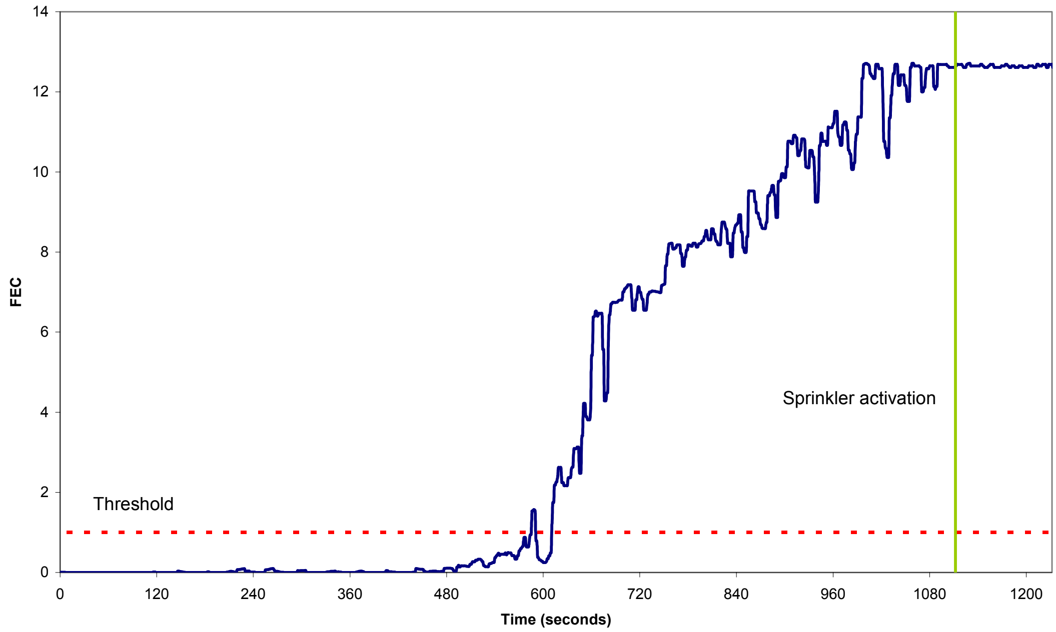


Figure 7.8.9: FEC$_{smoke}$ (Test 11 – 800 mm sampling height)

7.8.8. Test 12

No data was recorded from the analogue smoke and fire detectors during this test. The ignition method in this test was Method 2. It is worth noting that the sprinkler activated in just 217 seconds. This represents a particularly fast sprinkler activation time. Figure 7.8.11 shows the HRR curve for this fire. The graph shows that the fire displays a fast growth rate commencing less than 2 minutes after ignition and reaching a peak HRR of 200 kW about 100 seconds later when the sprinkler activated. Under these circumstances early activation of a fast response sprinkler head would not be unexpected.

Figure 7.8.12 shows the FEC_{smoke} graph for this test. The FEC_{smoke} threshold is not exceeded until just after sprinkler activation, at which time it climbs to over 5 (OD/m = 1), before peaking above 12 (OD/m = 2.4), indicating near 100 percent obscuration. Once again an occupant attempting to escape the apartment following sprinkler activation would be significantly impaired by the degree of smoke obscuration.

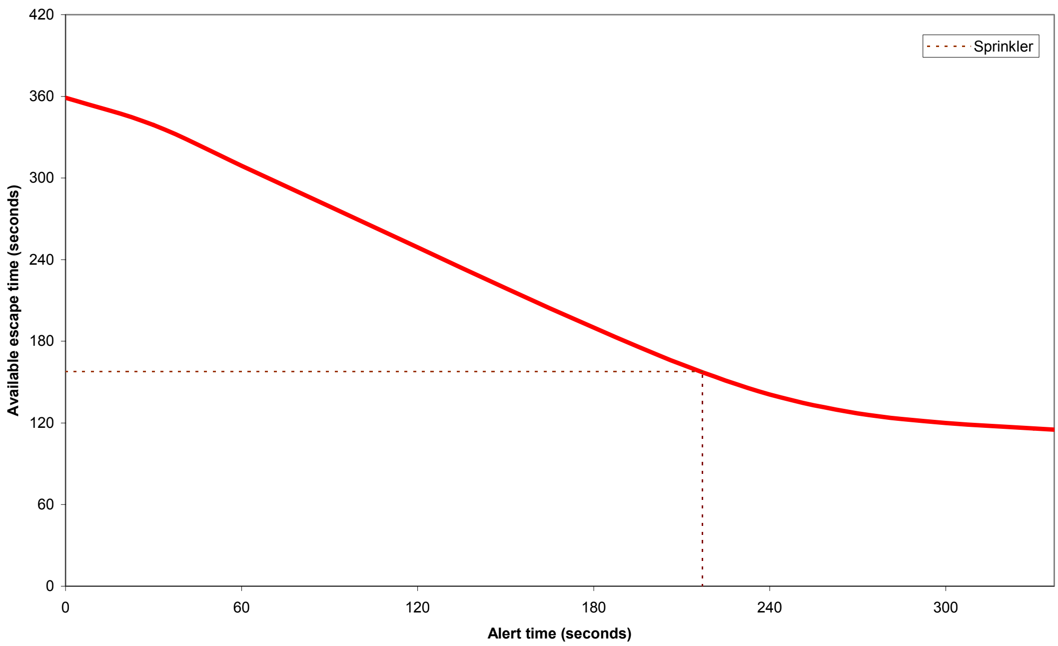


Figure 7.8.10: Alert time versus escape time (Test 12)

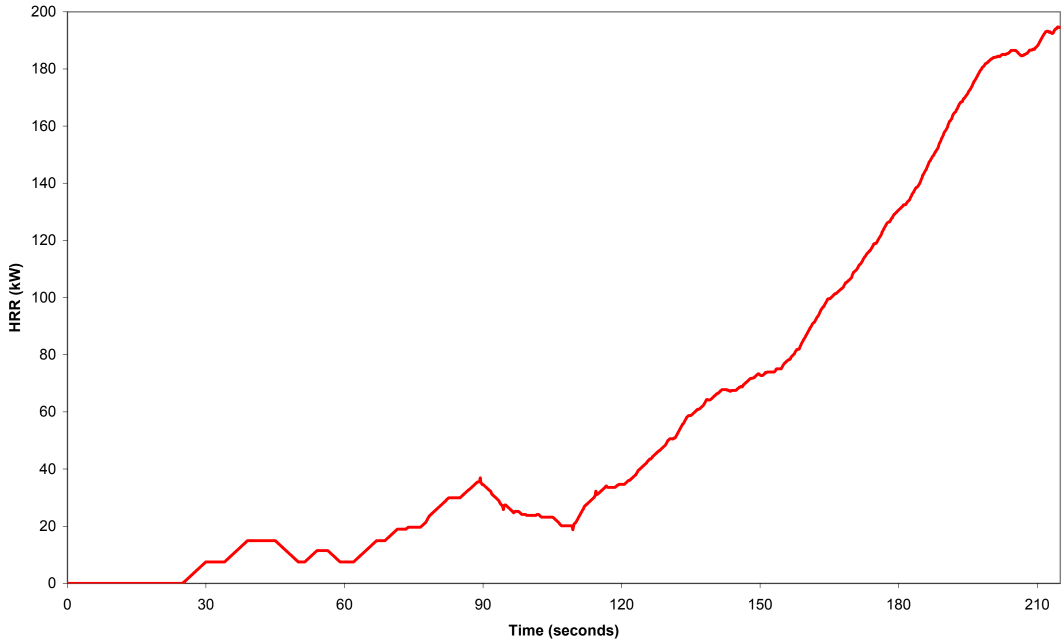


Figure 7.8.11: Heat release rate curve (Test 12)

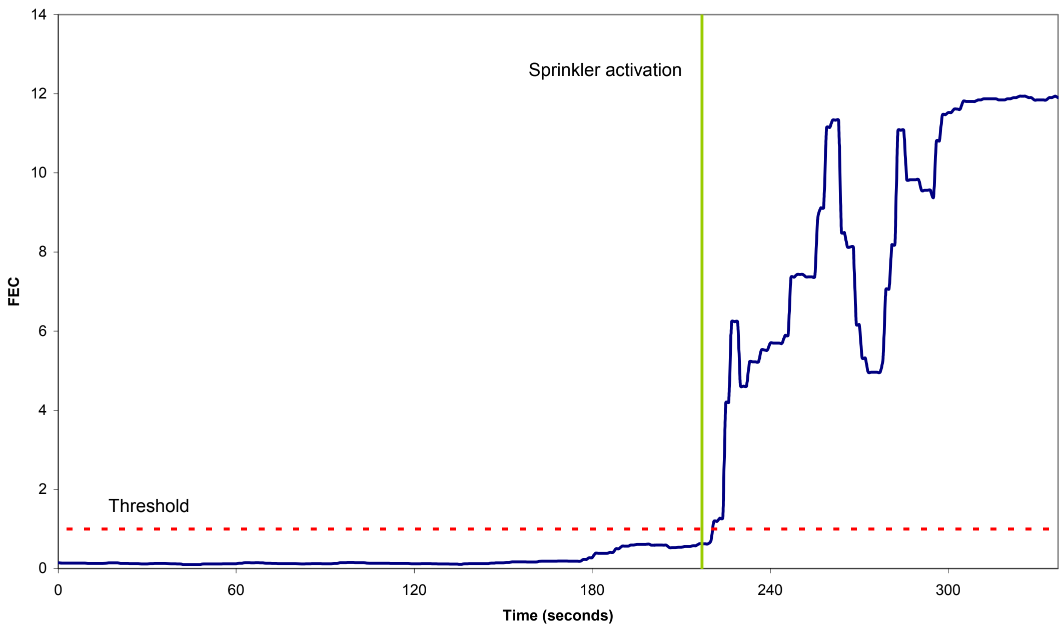


Figure 7.8.12: FEC_{smoke} (Test 12 – 800 mm sampling height)

7.8.9. Test 13

The ignition method in this test was Method 3. This fire exhibited a fairly moderate growth rate that commenced approximately 6 minutes after ignition. The mass loss data indicates a peak HRR of only 55 kW when the sprinkler activated 13 minutes into the fire.

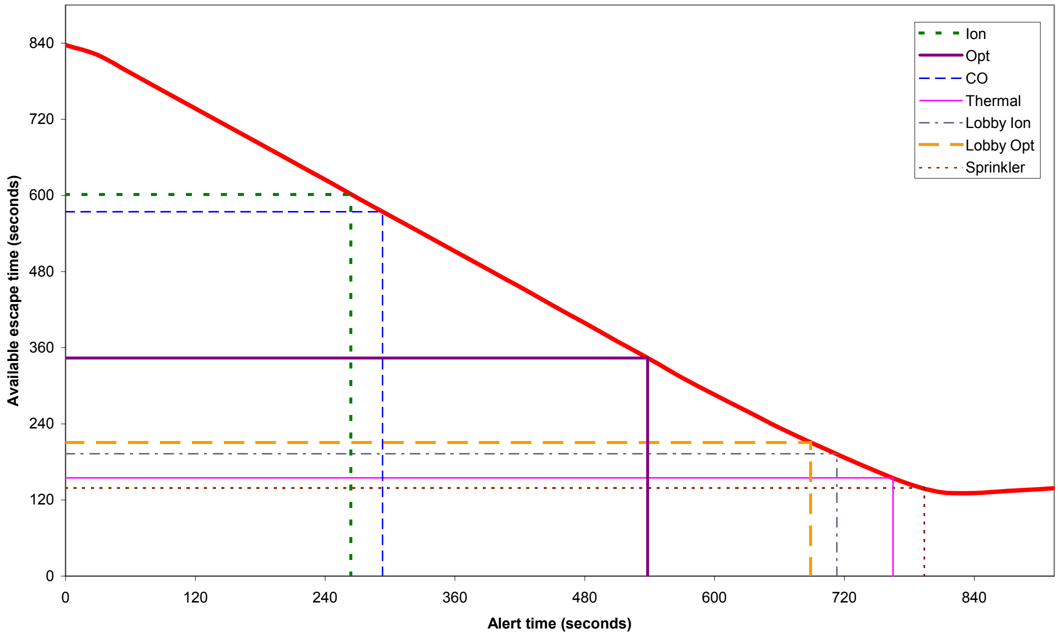


Figure 7.8.13: Alert time versus escape time (Test 13)

The FEC_{smoke} threshold was exceeded at 645 seconds (see Figure 7.8.14). This means that an occupant relying on either the thermal detector, smoke detectors in adjacent rooms, or the sprinkler system for warning of fire would have significant trouble attempting to escape due to the low visibility caused by smoke logging.

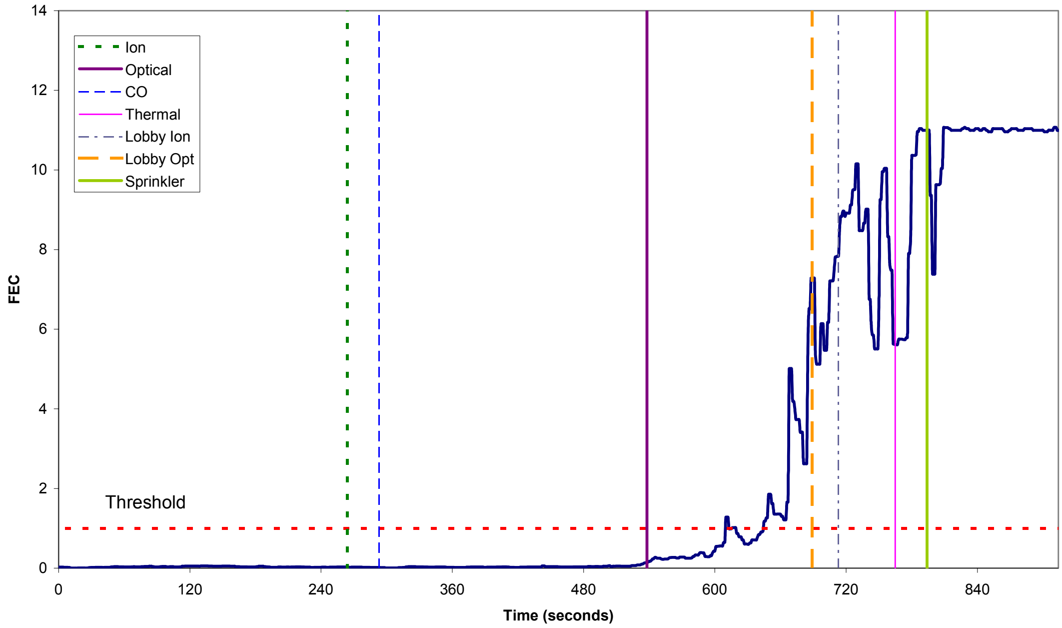


Figure 7.8.14: FEC$_{smoke}$ (Test 13 – 800 mm sampling height)

7.8.10. Test 14

This TV was easily ignited using Method 1, however it remained in an incipient stage for the first 6 minutes following ignition. At this point it commenced to grow at a very fast rate, peaking at 140 kW following sprinkler activation 9:30 minutes after ignition.

FEC_{smoke} at a sampling height of 1600 mm exceeded the threshold in 483 seconds. This means that occupants attempting to escape following activation of the thermal detector, two adjacent room smoke detectors, or sprinkler system would be significantly impaired by smoke obscuration t this height. Figure 7.8.16 indicates that almost total obscuration occurred prior to sprinkler activation.

In this test the optical detector in the compartment activated after the sprinkler operated. This result is significantly different from the activation responses in any other test, and while it may be a result of the fire conditions, it is also possible that contamination from previous tests has effected the detector's response. Figure 7.8.17 shows the fire safety system responses to this fire.

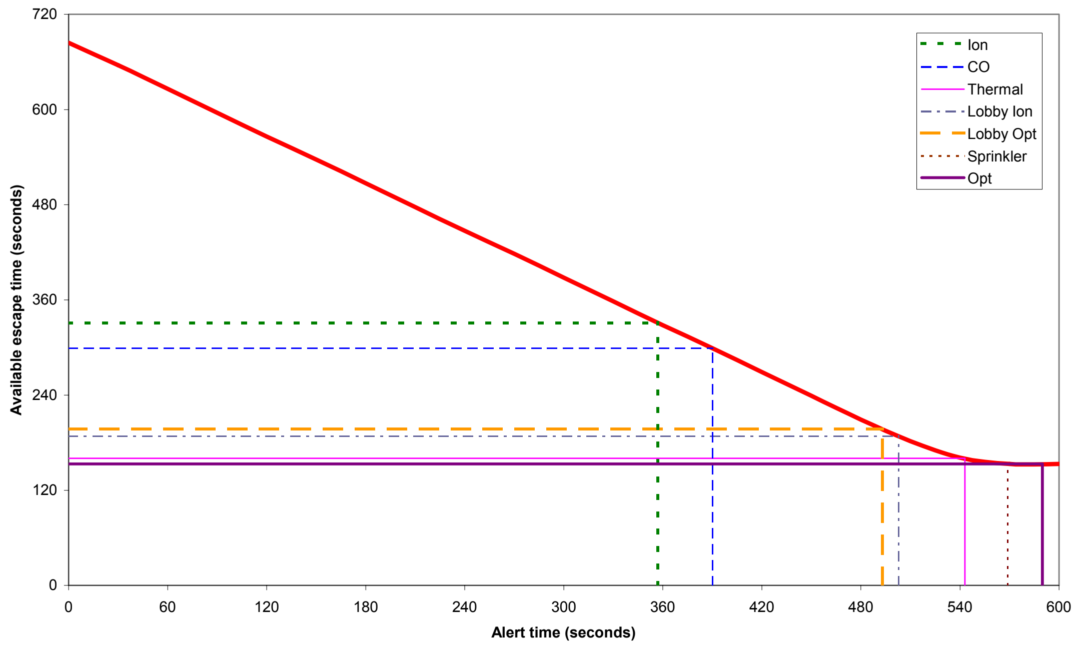


Figure 7.8.15: Alert time versus escape time (Test 14)

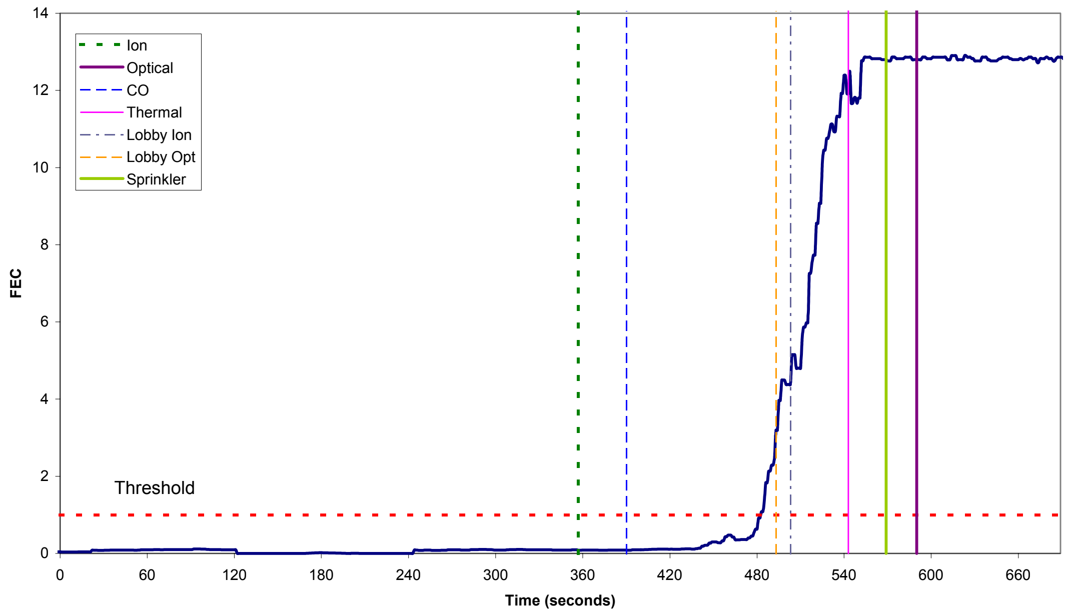


Figure 7.8.16: FEC$_{smoke}$ (Test 14 – 1600 mm sampling height)

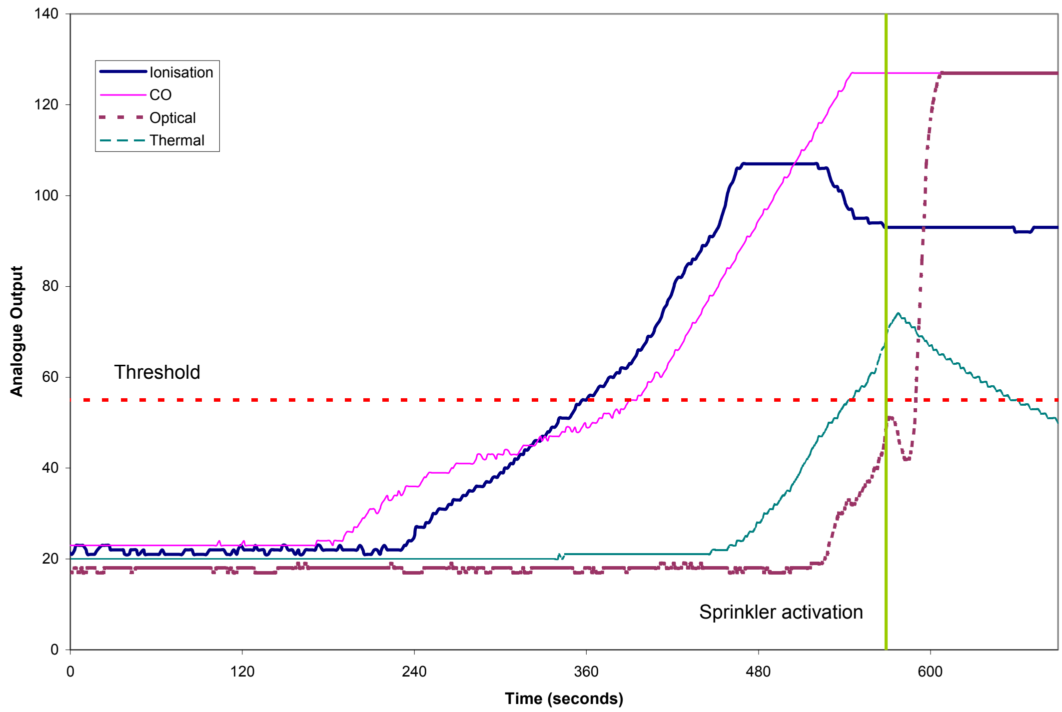


Figure 7.8.17: Fire safety system response (Test 14 – Compartment)

7.8.11. Test 15

Method 1 was used to ignite the TV set in this test. This television appeared to have a low HRR. Development commenced approximately 4 minutes into the fire, however after initially growing strongly the fire reached a peak of 90 kW and then proceeded to steadily decay. The sprinkler did not activate and the test was terminated after 30 minutes.

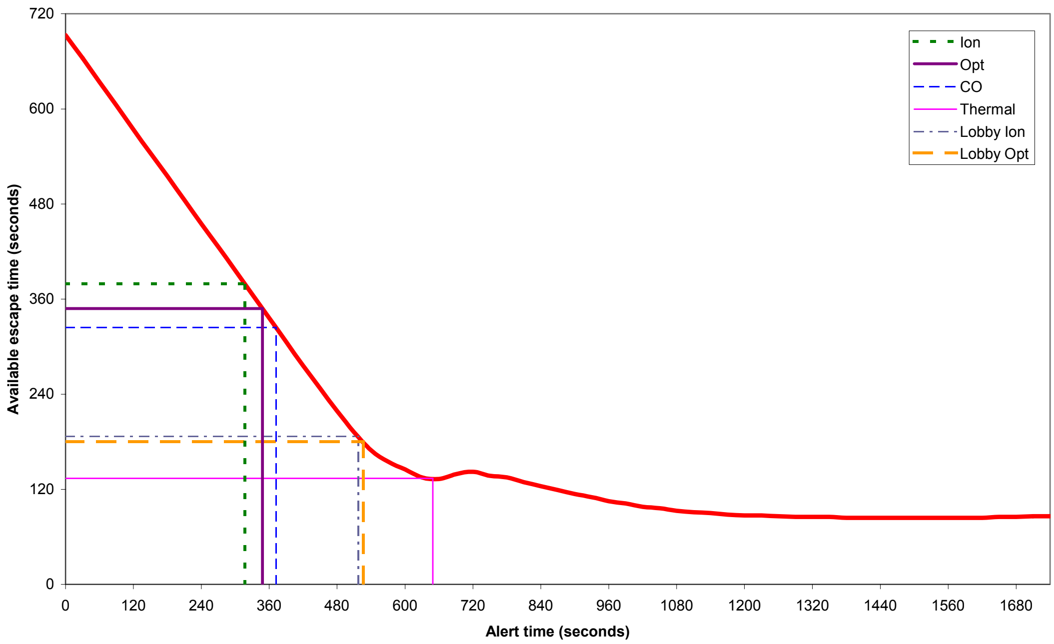


Figure 7.8.18: Alert time versus escape time (Test 15)

The FEC_{smoke} threshold at 1600 mm is exceeded in this test after 442 seconds as the smoke layer descends into the compartment (see Figure 7.8.19). As with the proceeding tests, the threshold is exceeded prior to activation of the thermal detector and the lobby smoke detectors. Escape attempts following an alert from these devices would be significantly hampered by smoke obscuration.

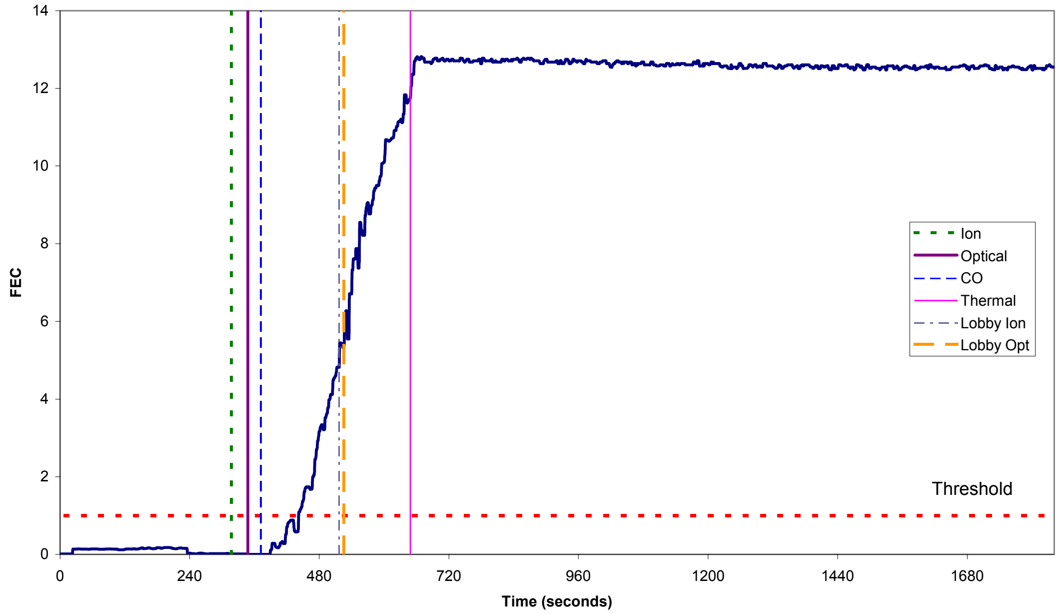


Figure 7.8.19: FEC$_{smoke}$ (Test 15 – 1600 mm sampling height)

7.8.12. Test 16

This TV was easily ignited using Method 1. The incipient phase continued for about 7 minutes before the fire displayed a very fast growth rate, peaking at 175 kW upon sprinkler activation 8:40 minutes after ignition.

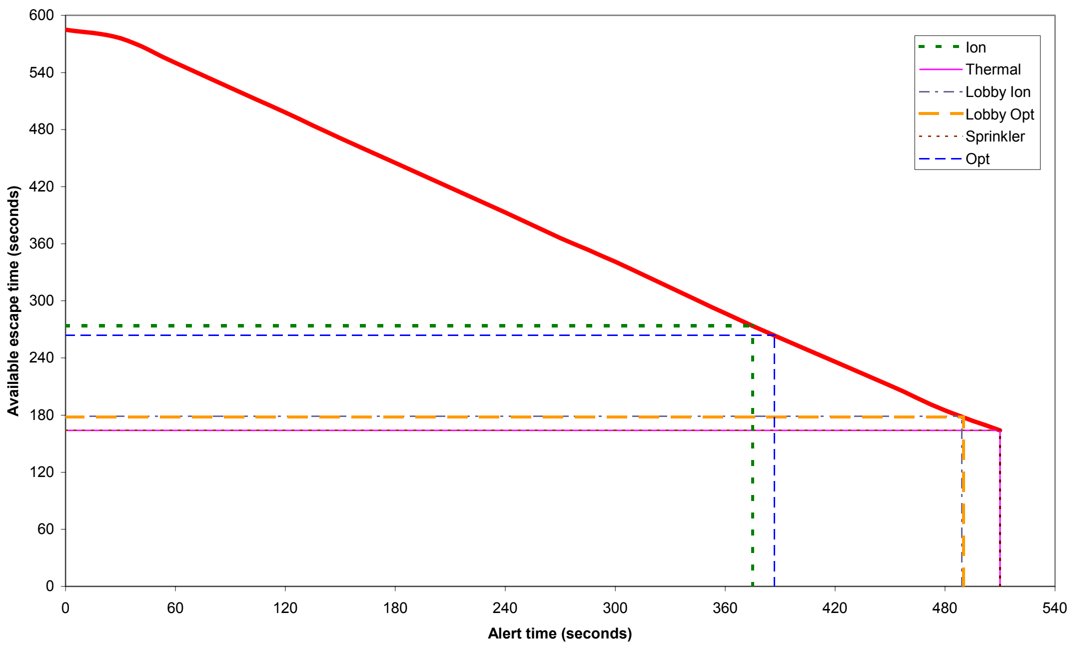


Figure 7.8.20: Alert time versus escape time (Test 16)

In this test the FEC_{smoke} threshold is exceeded in 463 seconds. Reliance on the thermal detector, lobby smoke detectors and sprinkler to provide warning would result in an escape attempt through a heavily smoke logged compartment.

It is worth noting that in this test visual impairment might also be experienced following an alert by the smoke detectors inside the compartment, depending on the pre-movement time. Both smoke detectors inside the compartment activated less that 100 seconds before the FEC_{smoke} threshold was reached at the 1600 mm sample height.

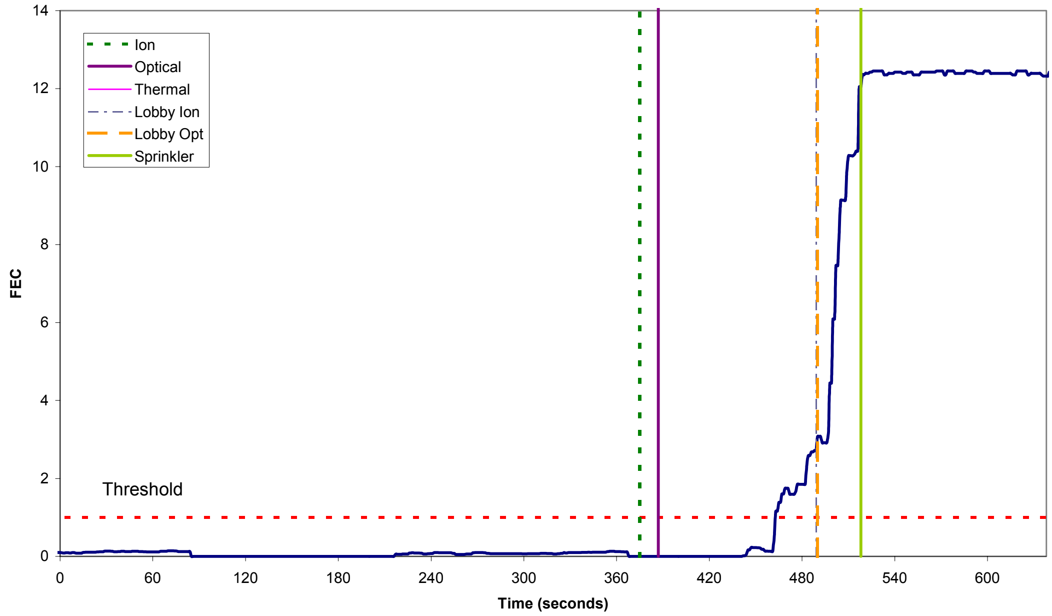


Figure 7.8.21: FEC$_{smoke}$ (Test 16 – 1600 mm sampling height)

7.8.13. Test 17

Ignition Method 3 was required to achieve sustained combustion in this test. The fire started to grow rapidly at the 2 minute mark, however after peaking at about 75 kW, it settled into a steady state phase that fluctuated between 40 - 60 kW. After 10 minutes the fire started to decay steadily. The sprinkler did not operate, and the test was terminated at the 23 minutes.

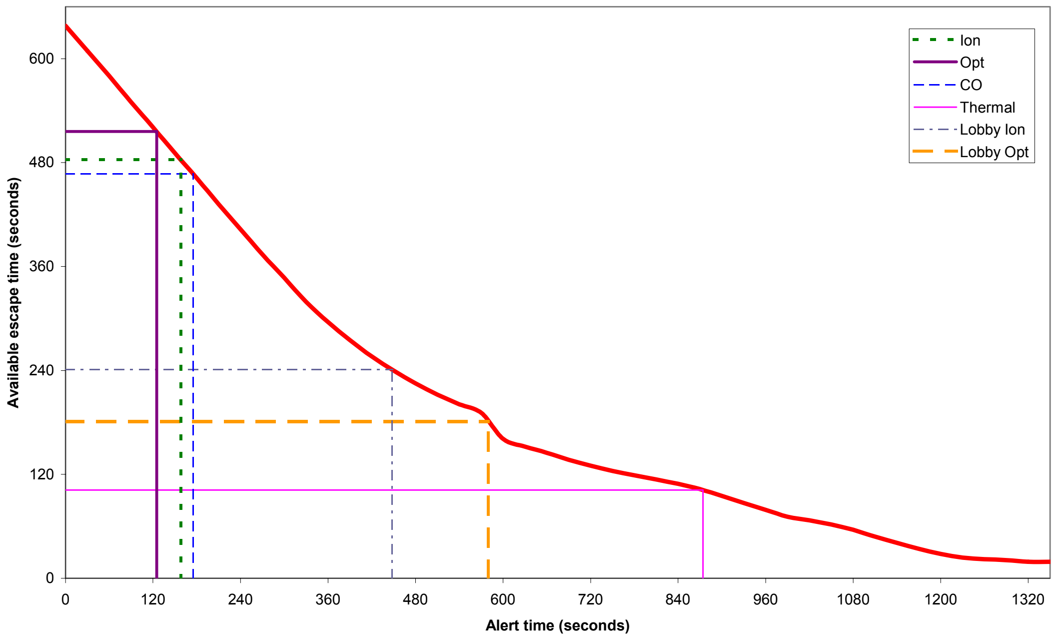


Figure 7.8.22: Alert time versus escape time (Test 17)

FEC_{smoke} exceeded to threshold value of 1.0 within 330 seconds of the start of the fire. Almost total visual obscuration occurred within 487 seconds. Escape attempts following activation of the thermal detector or either of the lobby smoke detectors would be significantly impaired by the level of smoke obscuration.

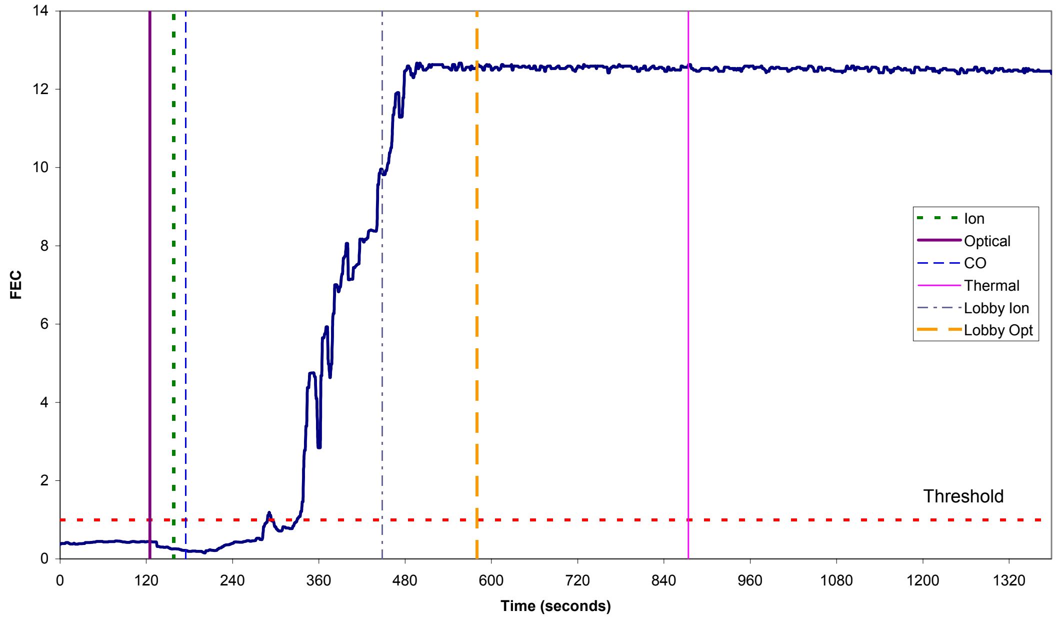


Figure 7.8.23: FEC$_{smoke}$ (Test 17 – 800 mm sampling height)

7.8.14. Test 20

Method 3 was required to achieve sustained combustion in this test. Fire development commenced 4 minutes after ignition, with a slow growth rate that peaked somewhere between 80 and 120 kW after 22 minutes. From this point on the fire slowly decayed. The sprinkler did not activate and the test was terminated after 40 minutes.

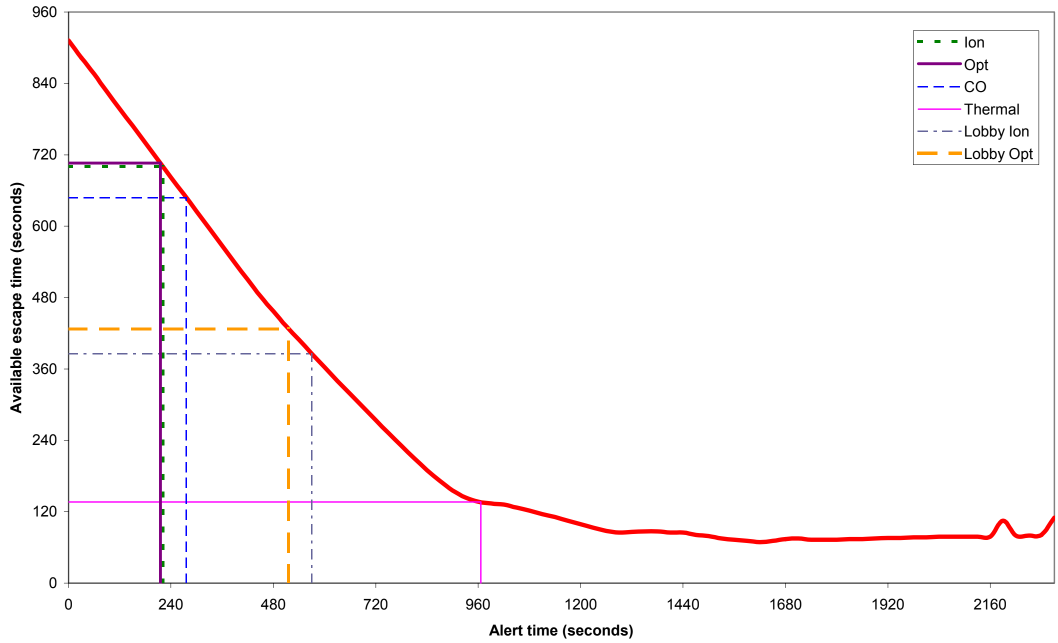


Figure 7.8.24: Alert time versus escape time (Test 20)

In this test the FEC_{smoke} threshold is exceeded after 505 seconds (see Figure 7.8.25). 100 percent obscuration occurs at around 700 seconds. Once again any occupants attempting escape following warning from the thermal detector, lobby smoke detection and sprinkler system would experience considerable difficulty due to loss of visibility.

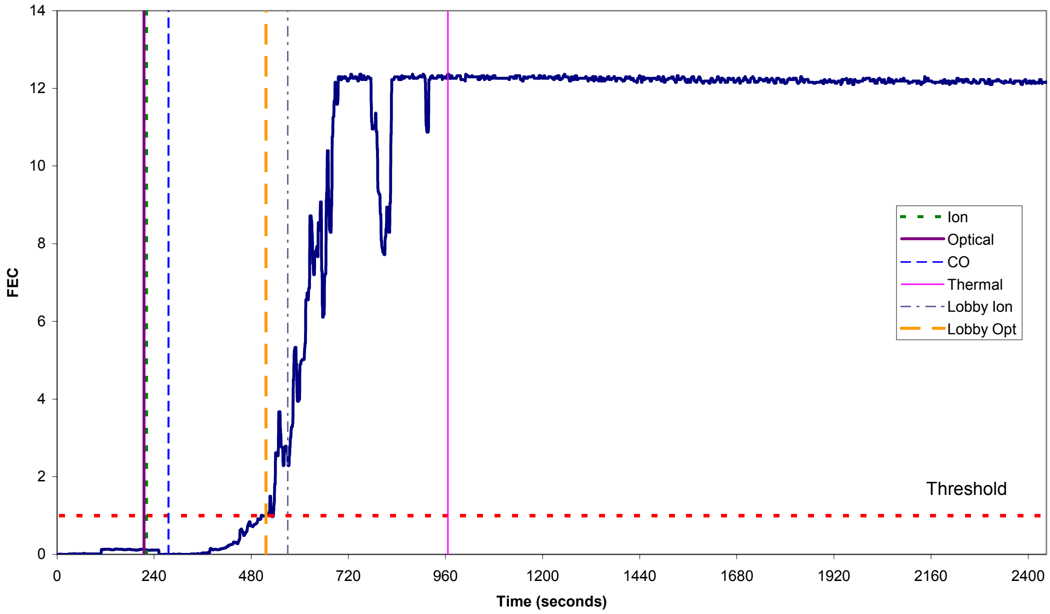


Figure 7.8.25: FEC$_{smoke}$ (Test 20 – 800 mm sampling height)

Table 7.8.1: Alert time versus available escape time summary (Table 1)

	Ionisation (seconds)		Optical (seconds)		CO (seconds)		Thermal (seconds)	
Test	Alert	Escape	Alert	Escape	Alert	Escape	Alert	Escape
1	510	545	412	643	565	495	907	158
2	420	1880	439	1861	1012	1312	3170	72
5	495	542	676	362	494	543	1006	126
6	424	358	421	361	440	342	734	92
7	357	425	335	446	331	450	662	149
8	189	538	193	534	227	500	879	107
11	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-
13	264	602	538	344	293	575	765	155
14	357	331	590*	153	390	299	543	160
15	317	379	348	348	372	324	649	134
16	375	274	387	318	?	?	518	126
17	158	483	125	516	175	467	874	102
20	221	700	215	706	276	648	966	136

* Reading possibly affected by contamination from previous tests

- : No measurements made ? : Problem with output

Table 7.8.2: Alert time versus available escape time summary (Table 2)

	Lobby Ion (seconds)		Lobby Optical (seconds)		Sprinkler/End (seconds)	
Test	**Alert**	**Escape**	**Alert**	**Escape**	**Alert**	**Escape**
1	-	-	-	-	995	84
2	-	-	-	-	3315	48
5	-	-	-	-	DNA	34‡
6	-	-	-	-	798	62
7	-	-	-	-	1333	27
8	-	-	-	-	DNA	18‡
11	-	-	-	-	1112	201
12	-	-	-	-	217	158
13	703	192	689	211	794	139
14	503	188	493	197	569	153
15	517	187	526	180	DNA	86‡
16	489	179	490	178	518†	164
17	448	241	580	181	DNA	19‡
20	570	386	516	427	DNA	110‡

† Alert time taken as 510 due to end of data

‡ Alert time taken as time test was terminated

DNA : Did Not Activate - : No measurement made

8. Discussion

The objective of this study is to examine what consequences the removal of smoke detection from the escape route will have on the ability of an occupant to safely evacuate from the apartment. Smoke detection represents the level of safety currently required in the escape route of a typical multi-storey apartment building under the deemed to satisfy provisions of the building code. Therefore any analysis should start by comparing the results with the level of safety afforded by smoke detection. It follows that if a fire safety system used in lieu of smoke detection provides an equivalent level of safety then it should also satisfy the performance requirements of the building code [50]. A comparison of the available escape times provided by each system against that provided by the smoke detectors is discussed in Section 8.1.

It must be recognised however that the deemed to satisfy requirements of the building code are intended to be applied in a generic manner, and consequently must incorporate a substantial safety factor. The question therefore remains as to whether a fire safety system used as part of a specific fire engineering design to replace smoke detection can offer a sufficient level of safety to meet the performance requirements of the building code, even if it does not achieve equivalency with the smoke detection system. Addressing this question will require an analysis of not only the available escape time, but also of the required escape time. This issue is discussed in detail in Section 8.2.

8.1. Comparison with Deemed to Satisfy Provisions

The available escape times provided by each fire safety system in each test are presented in Figure 8.1.1. For the purposes of comparison the ionisation detector has been used as the base measurement, as this is representative of the level of safety deemed to satisfy the performance provisions of the building code and has less uncertainty associated with its results than the optical detector.

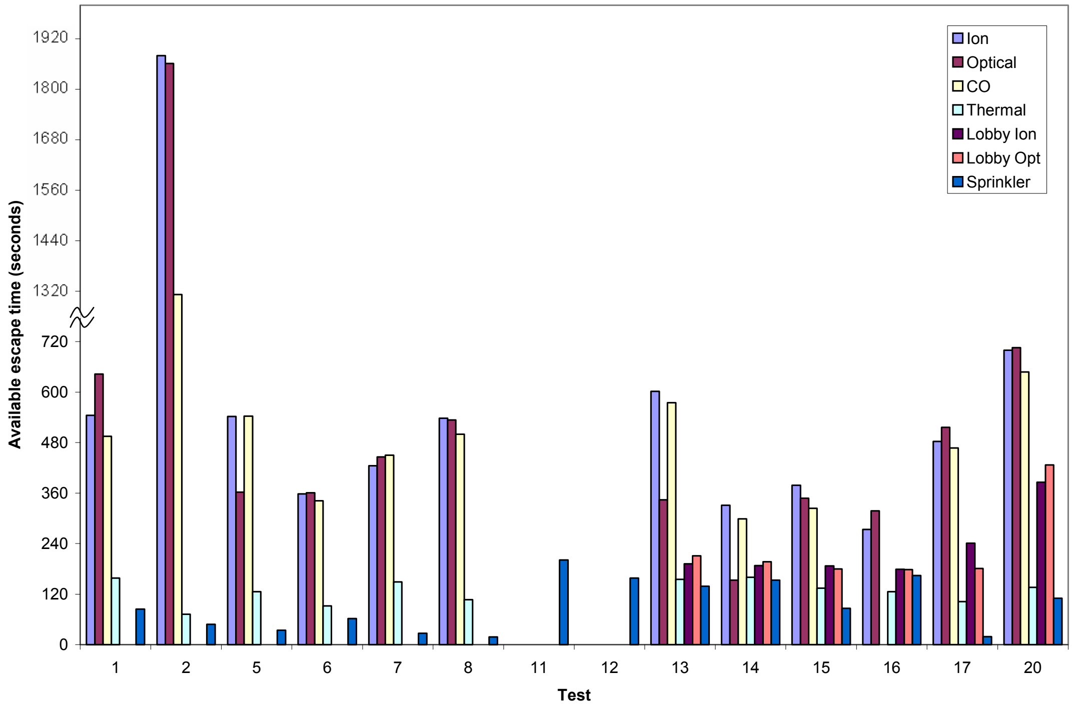


Figure 8.1.1: Available escape time at activation of fire safety system

Table 8.1.1 below shows the minimum, maximum and mean available escape times for each system over all the tests in which the FED threshold was exceeded, and then presents the performance of each system as a percentage reduction in the available escape time compared to that provided by the ionisation detector.

The results show that both the optical detector and the CO detector are capable of performing better than the ionisation detector, although on average they offered a reduction in available escape time, albeit by only 8 percent. It is interesting to note that the optical detector on one occasion provided over 50 percent less available escape time, although in this case (Test 14), the possibility of contamination from previous tests should be considered. The mean response time of the CO detector was less than a minute slower than the ionisation detector, and the minimum available escape time it provided was actually greater than the minimum provided by the ionisation detector.

Therefore based on this comparison, the performance of the CO detector is sufficiently close to that of the smoke detectors that it must be considered an adequate substitute for traditional smoke detection, at least under the fire scenario used for these tests. This in turn implies that it has demonstrated equivalency with the deemed to satisfy provisions of the building code. It is important to recognise that this conclusion is restricted to the conditions under which the tests were conducted, and does not necessarily mean that the CO detector would provide satisfactory performance under other fire scenarios. It is also important to recognise that this evaluation is restricted to a single model of CO detector, and does not allow any conclusions to be drawn regarding the performance of CO detectors in general. Nor does it address issues such as the testing, maintenance and reliability of CO detectors.

Table 8.1.1: Summary of reduction in available escape times in comparison to ionisation detector

	Available escape time (seconds)			Reduction in available escape time compared to ion detector		
System	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**
Ion	274	1880	588	-	-	-
Optical	153	1861	549	-18%	54%	8%
CO	299	1312	541	-6%	30%	8%
Thermal	92	160	126	52%	96%	72%
Lobby Ion	179	386	229	35%	68%	49%
Lobby Opt	181	427	229	35%	65%	49%
Sprinkler	18	201	93	40%	97%	81%

In contrast to the CO detector, the thermal detector provided significantly reduced available escape times, on average allowing 72 percent less available escape time, and up to 96 percent less. It real terms this meant the thermal detector provided less than 3 minutes of available escape time in all tests, in comparison to the minimum of 4:30 minutes provided by the ionisation detector. This deviation from the performance of the ionisation detector is so substantial that the thermal detector cannot be considered to provide an equivalent level of safety under this fire scenario.

The performance of both lobby detectors is very similar to one another, and both provide a mean reduction in available escape time of approximately 50 percent when compared to the ionisation detector located in the compartment. This is not unexpected as the closed door between the fire compartment and lobby space presents a significant impedance to smoke reaching the detectors. It would therefore be unrealistic to expect an equivalent level of safety from similar systems in a physically separate space. However despite this handicap, they still provided a minimum available escape time of around 3 minutes and out performed the thermal detector located in the compartment. Although as discussed later, this may in part be the result of generous gaps in the door set connecting the two spaces.

Not surprisingly, the sprinkler system provides the greatest reduction in available escape time compared to the ionisation detector. The mean reduction is over 80 percent, and minimum available escape time afforded by the sprinkler system is only 18 seconds. Therefore the sprinkler does not represent an equivalent level of safety to the deemed to satisfy provisions of the building code. It should be noted that in 5 cases the sprinkler did not activate, and so the available escape time is taken at the end of the test in these cases (this includes the worst case result of 18 seconds). The tests were called off when static conditions were observed in most measuring equipment, however this still represents an arbitrary time in the fire.

8.2. Comparison of Available Escape Time with Required Escape Time

While this study has focused on quantifying the available escape times in the scenario for the various fire safety systems experimentally, previously published literature will have to be relied on to provide the required escape time. Results of both the FEC_{smoke} calculations and visual observations of the tests indicate that an occupant attempting to escape the apartment during the latter stages of the fire will be confronted by very dense smoke. Jin [14] suggests that at an OD/m of 0.2 (OD of 0.5 1/m) in irritant smoke, walking speed will be reduced to 0.3 ms^{-1}. Proulx [32] details a study by Jensen indicating that at an OD/m of 0.47 (OD of 1.09 1/m), movement speed was around 0.2 ms^{-1}.

The FEC_{smoke} threshold of 1.0 equates to an OD/m of 0.2, which allows an assessment to be made of the likely movement speed of an occupant attempting to escape through the fire compartment during the tests. In the majority of tests, the smoke layer descended in a fairly uniform manner, leaving relatively clear visibility below. This is confirmed by the FEC_{smoke} graphs which show a rapid increase in visual obscuration as the smoke layer descends past the level at which the measurements were taken. Therefore in order to simplify the analysis, it has been assumed that visibility is not significantly compromised prior to the FEC_{smoke} threshold being exceeded. A commonly accepted walking speed of 1.2 ms^{-1} [14] has been selected for movement prior to FEC_{smoke} reaching 1.0. This is somewhat generous because if the smoke layer is quite low (i.e. approaching the 800 mm sampling height), then the occupant may be forced to crouch or crawl to remain beneath the smoke layer. This in turn may slow their movement speed even if visibility is not reduced.

A worst case travel distance would involve entry and exit doors that were at opposing ends of the compartment. If it is assumed that the occupant has very limited visibility and therefore needs to follow the wall to navigate the compartment, then the maximum travel distance would be about 12 metres (8 m along the side wall + 4 m along the end wall). In good visibility this distance could be travelled in 10 seconds (12 m at 1.2 ms^{-1}). Of course in good visibility the occupant would not be required to follow the walls, however the time of 10 seconds is deemed reasonable. In heavy smoke conditions at a speed of 0.3 ms^{-1} it would take 40 seconds to exit the room, and a speed of 0.2 ms^{-1} would require 60 seconds. For this analysis the average of these values has been used, giving a required escape time of 50 seconds for $FEC_{smoke} \geq 1.0$.

The activation times of each fire safety system are shown on the FEC_{smoke} graphs in Section 7.8, and the activation times are compared to the time at which the FEC_{smoke} threshold is exceeded for each test in Table 8.1.1 and Table 8.2.2 below. It should be noted that comparisons are only possible for those tests in which visual obscuration measurements were taken (Tests 11 to 20). The alert time is subtracted from the FEC_{smoke} threshold time to give the reduced visibility time (RVT) following activation of each system. A positive RVT provides the amount of time available to escape in good visibility conditions (i.e. the required escape time is 10 seconds). A negative RVT value indicates that the FEC_{smoke} threshold has been exceeded prior to the activation of the system, and therefore escape would be through heavy smoke conditions with reduced movement speed (i.e. the required escape time is 50 seconds).

It is important to note that pre-movement time plays an crucial role in determining what conditions face the occupant when they attempt to escape through the living area. If the amount of time taken for the occupant to respond to the alert exceeds the RVT, then movement through the fire compartment will be impaired by smoke obscuration. Pre-movement time is not easy to quantify, and will be dependant on the individual circumstances and characteristics of the occupant, i.e. asleep or awake, sober or intoxicated. However for the purposes of this analysis a pre-movement time of 30 seconds has been assumed. This is a qualitative assessment, and considers that an occupant would have an immediate vested interest in responding to an alert from within their place of residence. If however the apartment building has been subjected to numerous unwanted alarm activations, the occupants may have developed an attitude of complacency, in which case pre-movement times could be significantly longer. Nevertheless, using a pre-movement time of 30 seconds implies that for any RVT ≤ 30 seconds, the required escape time will be 50 seconds. FEC_{smoke} thresholds that are exceeded while evacuation is in progress have been ignored.

Table 8.2.1: Alert time versus FEC_{smoke} threshold time (Table 1)

		Ionisation (seconds)		Optical (seconds)		CO (seconds)		Thermal (seconds)	
Test	**FEC_{smoke}**	**Alert**	**RVT**	**Alert**	**RVT**	**Alert**	**RVT**	**Alert**	**RVT**
11	611	-	-	-	-	-	-	-	-
12	222	-	-	-	-	-	-	-	-
13	645	264	381	538	107	293	352	765	-120
14	483	357	126	590	-107	390	93	543	-60
15	442	317	125	348	94	372	70	649	-207
16	463	375	88	387	76	-	463	518	-55
17	330	158	172	125	205	175	155	874	-544
20	505	221	284	215	290	276	229	966	-461

- : No measurements made

Table 8.2.2: Alert time versus FEC_{smoke} threshold time (Table 2)

		Lobby Ion (seconds)		Lobby Opt (seconds)		Sprinkler (seconds)	
Test	**FEC_{smoke}**	**Alert**	**RVT**	**Alert**	**RVT**	**Alert**	**RVT**
11	611	-	-	-	-	1112	-501
12	222	-	-	-	-	217	5
13	645	703	-58	689	-44	794	-149
14	483	503	-20	493	-10	569	-86
15	442	517	-75	526	-84	DNA	-ve
16	463	489	-26	490	-27	518	-55
17	330	448	-118	580	-250	DNA	-ve
20	505	570	-65	516	-11	DNA	-ve

- : No measurements made

As expected, Table 8.2.1 and Table 8.2.2 reveal that escape following activation of the smoke detectors and CO detector within the compartment would occur in good visibility, and therefore take only 10 seconds. The solitary exception is the optical detector activation in Test 14. As previously discussed, this may well be an erroneous reading caused by contamination from earlier tests. In contrast, the FEC_{smoke} threshold is exceeded prior to the activation of the thermal detector, the two lobby smoke detectors and the sprinkler system, in every test. An occupant attempting to escape following an alert from any of these systems would therefore require 50 seconds to move through the living area.

Once the required escape times had been determined they could be compared with the available escape times in each test to ascertain whether an occupant could escape safely following warning provided by each fire safety system (i.e. ASET - RSET). This comparison is shown in Table 8.2.3, Table 8.2.4 and Table 8.2.5. Escape time commences upon exposure to the fire compartment, and this can be assumed to occur when the occupant opens the door between the adjacent space (presumably the bedroom) and the living area. If the FEC_{smoke} threshold has been exceeded at this point, it is likely that smoke will flow rapidly into the adjacent space, which would quickly become smoke logged as well. In this scenario an occupant disorientated from being unexpectedly awoken is then confronted by a rapid influx of heavy, dark smoke upon opening the door to the living room. Under these circumstances it is not difficult to imagine how disorientation and loss of visibility due to high optical smoke density and sensory irritation, along with respiratory distress from irritant smoke, might result in the occupant taking up to a minute to recover some degree of equilibrium and make the journey through even the familiar environment of their own living room.

It should be noted that required escape times for Test 1 to 8 are assumed, however a reasonable level of confidence can be taken from the consistency of required escape times for each type of system attained in Tests 11 to 20 (see Table 8.1.1 and Table 8.2.2). It is also important to note that unlike determining the required escape time, no account of pre-movement time has been made in the available escape time calculations. This is because the available escape time is only dependant on exposure to the fire compartment, and this does not occur until movement commences (i.e. the occupant opens the door to the fire compartment). It could be argued however that prolonged pre-movement time would decrease the available escape time, as the level of toxic products in the fire compartment increased. The alert time versus available escape time graphs contained in Section 7.8 allow the implications of difference pre-movement times to be evaluated.

Table 8.2.3: ASET versus RSET (Table 1)

	Ionisation (seconds)			Optical (seconds)			CO (seconds)		
Test	**ASET**	**RSET**	**Margin**	**ASET**	**RSET**	**Margin**	**ASET**	**RSET**	**Margin**
1	545	10	535	643	10	633	495	10	485
2	1880	10	1870	1861	10	1851	1312	10	1302
5	542	10	532	362	10	352	543	10	532
6	358	10	348	361	10	351	342	10	332
7	425	10	415	446	10	436	450	10	440
8	538	10	528	534	10	524	500	10	490
11	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-
13	602	10	592	344	10	334	575	10	565
14	331	10	321	153	10	143	299	10	289
15	379	10	369	348	10	338	324	10	314
16	274	10	264	318	10	308	-	-	-
17	483	10	473	516	10	506	467	10	457
20	700	10	690	706	10	696	648	10	638

- : No measurements made

Table 8.2.3 shows that in every case the available escape time exceeds the required escape time for the two compartment smoke detectors and the CO detector. The narrowest margin comes from the optical detector in Test 14, with a margin of 143 seconds. This result has already been identified as potentially erroneous, and if ignored, this means the minimum margin between the available escape time and the required escape time is 264 seconds (4 min 24 sec). Under these circumstances the three systems should be considered to meet the performance requirements of the building code.

Once again with regard to the CO detector, it is important to note that this conclusion is only valid for the conditions under which the test were conducted, and only for the model of detector evaluated. No substantive conclusions can be drawn about the suitability of CO detectors in general, however the results indicate that further study of their suitability as a replacement for smoke detectors is warranted.

Table 8.2.4 below reveals that for the lobby smoke detectors, the available escape time still exceeds the required escape time, however it this case the margin is much narrower than in the previous results. The minimum margin between available escape time and required escape time is 128 seconds. In determining whether this represents a sufficient level of safety, the following factors should be taken into consideration:

- The lobby used in the tests represents a best possible case in that the space was only 1.2 m^2, and the detectors were located within 600 mm of the connecting door. Both of these factors maximised the possibility of undiluted smoke entering the sensing chambers at the earliest possible time.

- The door set connecting the fire compartment with the adjacent space was not as well constructed as might be expected in a real apartment, and therefore more smoke probably entered the lobby, and at an earlier time than might normally be expected.

- The absolute values of both available and required escape times are small, therefore estimation errors of even 30 seconds could have a significant effect on the result. Given the uncertainties associated with human behaviour in fire, large safety margins would be recommended.

So while a minimum safety margin of just over 2 minutes appears reasonable, the concerns raised above indicate that caution is required. It would therefore be prudent to carry out further experimental evaluation before determining whether smoke detection in an adjacent space can be relied upon to allow an occupant to escape safely from this fire scenario.

Table 8.2.4: ASET versus RSET (Table 2)

	Lobby Ionisation (seconds)			Lobby Optical (seconds)		
Test	**ASET**	**RSET**	**Margin**	**ASET**	**RSET**	**Margin**
1	-	-	-	-	-	-
2	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	-
11	-	-	-	-	-	-
12	-	-	-	-	-	-
13	192	50	142	211	50	161
14	188	50	138	197	50	147
15	187	50	137	180	50	130
16	179	50	129	178	50	128
17	241	50	191	181	50	131
20	386	50	336	427	50	377

Table 8.2.5: ASET versus RSET (Table 3)

	Thermal (seconds)			Sprinkler/End (seconds)		
Test	**ASET**	**RSET**	**Margin**	**ASET**	**RSET**	**Margin**
1	158	50	108	84	50	34
2	72	50	22	48	50	-2
5	126	50	76	34*	50	-16
6	92	50	42	62	50	12
7	149	50	99	27	50	-23
8	107	50	57	18*	50	-32
11	-	-	-	201	50	151
12	-	-	-	158	50	108
13	155	50	105	139	50	89
14	160	50	110	153	50	103
15	134	50	84	86*	50	36
16	126	50	76	164	50	104
17	102	50	52	19*	50	-31
20	136	50	86	110*	50	60

* End time of test used because sprinkler did not activate

- : No measurements made

Table 8.2.5 shows that the thermal detectors provided an available escape time that exceeded the required escape time in all cases, however the margins were not substantial. In absolute terms the minimum difference between the available escape time and the required escape time was 22 seconds, and in no case did the difference exceed 2 minutes. Taking into consideration the previously discussed uncertainties regarding human behaviour and small absolute values, it is concluded that the thermal detector does not provide a sufficient level of safety to allow an occupant to escape the apartment under this fire scenario.

Table 8.2.5 shows that for the sprinkler system, the required escape time exceeded the available escape time in 5 cases. Of the remaining cases, the minimum difference between the available escape time and the required escape time was just 12 seconds, and the maximum margin was only 151 seconds. These results clearly indicate that the fast response residential sprinkler system does not provide a sufficient level of safety to allow an occupant to escape from the apartment under this fire scenario.

It should be remembered that Tests 14 - 16 involved sample heights of 1600 mm. It is possible that conditions at a height of 800 mm might provide longer available escape times, however inspection of Table 8.2.5 reveals that Tests 14 and 16 provide two of the more generous available escape times anyway. In Test 15 the sprinkler failed to operate, in which case it is likely that the tenability conditions would have stabilised in the compartment by the end of the test. It can also be argued that requiring an occupant to adopt a crawling position (i.e. 800 mm head height) in order to effect an escape does not provide a sufficient level of safety under the performance requirements of the building code, regardless of whether the escape attempt is successful.

It should also be noted that in the 5 cases where the sprinkler failed to operate, the end time of the test was used to calculate the available escape time. This represents a somewhat arbitrary point in the fire not related to any particular alert time, however it can be considered indicative of the toxic hazard present in the later stages of the fire. It does raise an interesting point regarding what would happen in this scenario if the television fire burned out completely and the occupant remained unaware of the fire for a considerable period of time. It is possible that sufficient toxic products could accumulate in the bedroom to eventually present a hazard in that space. Alternatively the tenability conditions in the fire compartment could remain static and present a threat when the occupant eventually enters the living room. A third option is that the toxic hazard in the living area is gradually diluted over time with the natural air change that occurs within the apartment. Smoke could also find its way into the corridor outside the apartment and may activate the smoke detection system there. However as the door from the apartment to the outside corridor is likely to be fire rated, it is uncertain how much smoke would pass into the corridor. While potentially of interest, it was not within the scope of this study to investigate these possibilities.

Tenability conditions were only measured for a maximum of two minutes after sprinkler activation. This limit was necessary to avoid flooding the test facility, however it did not allow an assessment to be made of the tenability conditions during sustained sprinkler discharge. While the $FED_{aphyxiant}$ graphs indicate that tenability appears to continue decreasing following sprinkler discharge (see Section 7.7), it is possible that sprinkler discharge might eventually lead to improved conditions within the fire compartment and increase the occupants chance of successfully escaping from the apartment. It should be noted that the sprinkler system as used in this study did not achieve the minimum specified flow rate. While this was not critical due to the short time the sprinkler was operating, if the effects of sprinkler operation are going to be measured over a longer duration, it is important that the system operates within its design parameters.

8.3. General Discussion

The results of this analysis are in reality not particularly surprising. Sprinklers and thermal detectors respond to heat, and therefore cannot be expected to perform well in a fire with a low heat release rate. While this is a commonly known fact, what has probably not been so well appreciated in the past is that untenable conditions can arise from a fire that does not produce sufficient heat to activate even a fast response sprinkler system. So while heat release rate can be considered the most significant predictor of fire hazard [51], this study shows that it should not be viewed in isolation. Likewise the effects of ‘downdrag’ following sprinkler activation are also well known. However once again the assumption has generally been that with a fast response sprinkler there would be insufficient build up of combustion products in the upper layer prior to activation to present significant problems, either in terms of visibility or toxicity. The results of this study have shown that in regard to some plastics fires with low heat release rates, this assumption cannot be relied upon.

It is important to recognise that it is not the purpose of this report to discredit the performance of sprinkler systems, especially fast response residential systems, which perform an extremely important life safety and property protection function within residential buildings. The concerns addressed in this report have been raised in response to the removal of another fire safety system which is designed to work in a complementary manner with the sprinkler system to provide a comprehensive level of safety over a wide range of fire scenarios.

Removing smoke detection from the means of escape within residential apartments, without providing a suitable alternative, risks placing the fast response sprinkler system in a role it was neither designed for, nor is necessarily suited to. This in turn can lead to the possibility of the sprinkler system 'failing' because it has been called upon to perform a function that is outside of its operating parameters. Nevertheless, it must be recognised that there are significant unwanted activation problems associated with the use of smoke detection in the living areas of small apartments, and if the removal of early detection is not a viable option, efforts must be made to find an acceptable alternative.

Exploring the suitability of alternatives such as CO detectors should be given a high priority, along with more sophisticated smoke detectors that offer multi-criteria heads and false alarm defeating algorithms, multiple sensitivity levels and rapid drift compensation. Reducing the build up of fumes in the apartment is also part of the solution, so improved ventilation, and in particular the use of non-recirculating kitchen rangehoods would significantly contribute to the reduction in unwanted activations. The provision of mute buttons in a readily assessable position would mitigate the effects of any unwanted activation. Finally care in the positioning of smoke detectors outside apartment doors is necessary to ensure that any fumes escaping the apartment when the door is opened do not trigger a corridor detector.

It is important to recognise that a number of factors influence the decision as to what constitutes an acceptable fire safety system, other than just response performance. This study did not take into consideration such aspects as reliability, in which sprinkler systems have an exemplary record. Nor did it consider the issue of system maintenance. The servicing interval for a sprinkler system is much greater than that for most detection systems, and this has implications both in terms of gaining access to individually tenanted spaces, as well as the ongoing costs associated with the system.

It is obvious from the results in Section 8.1 that removing the smoke detection from the escape route and relying solely on the fast response residential sprinkler system does not provide an equivalent level of safety to the deemed to satisfy provisions of the building code. It is also apparent from the analysis in Section 8.2 that sprinklers alone do not provide a sufficient level of protection to allow an occupant to safely escape in the event of this fire scenario. However if a risk based approach is taken to the specific fire engineering solution, then the probability of the fire scenario occurring must also be considered, along with the consequence, when determining if the design meets the performance requirements of the building code. While this study has attempted to quantify the consequences of this fire scenario on occupant safety, it was not within the scope of the research to assess the probability of this type of fire scenario occurring in the first place.

Previous studies indicate that televisions account for a low proportion of electrical fires in dwellings (see Section 2.3). New Zealand Fire Service statistics show that 267 fires were attributed to TV sets and a further 96 to computers in the past 10 years [52]. This would tend to support the view that the overall risk is quite small, however further research into the probability of fires involving TV sets, computer monitors and any other scenarios that product similar results would be required before an accurate picture of the actual risk can be established.

8.4. Further Work

Although data was collected from a total of 20 tests, circumstances meant that it was rarely possible to get comprehensive measurements for every test. As it is difficult to draw any firm conclusions from a limited set of samples, this study would benefit from further tests of a similar nature that collected the full range of data for each test. In particular reliable confirmation on the concentration of hydrogen cyanide, and the contribution of irritants such as hydrogen chloride would be useful, along with lobby detector tests using a more tightly fitting connecting door. It would also have been beneficial to explore the impact of sustained sprinkler discharge on tenability conditions. For this to be effective, the system flow and pressure must be within the parameters specified by the manufacturer. The importance of visual obscuration on the required escape time means that optical density measurements are critical to a comprehensive analysis.

A closer examination of the performance requirements of the building code would also be warranted in regard to establishing experimental parameters. For example in this study a sampling height of 800 mm has generally been used, as this represents the likely height of an occupant attempting to escape under the smoke layer where it is expected that the air will clearer and visibility greater. However this in itself may present too great a compromise to satisfy the performance requirements of the building code. If an occupant cannot walk to safety, then it is possible that the performance requirements have not been met. Therefore perhaps any further experimental work should assume a sampling height of around 1600 mm as representative of an upright adult.

If the conclusion of this report is that fast response residential sprinklers cannot be safely used in lieu of smoke detectors, then it is important to find a suitable replacement that is not subject to the same degree of unwanted activation as currently plagues smoke detection systems in small living spaces. Although CO detectors appeared to offer a suitable alternative, further work would be necessary on their response to other fire scenarios, as well as their susceptibility to cooking fumes and other causes of unwanted activations. The testing, maintenance, reliability and cost issues associated with CO detectors would also need further investigation before they could be considered as a serious alternative.

Reducing the susceptibility of tradition smoke detection to unwanted activations is another solution that needs urgent investigation. The use of more sophisticated systems, i.e. those with fuzzy logic capable of recognising the signature of cooking fumes, and/or systems with combination detectors may resolve the problem.

The tests raised some interesting questions regarding the risk posed by televisions sets in fires, and further investigation into the flammability of television sets sold in New Zealand would be worthwhile. It appears from the tests that the vast majority of the sets used did not meet the V-0 fire retardancy classification. This raises the argument over whether the contribution of fire retardants to the toxicity of a fire, and the environmental hazard they present, is outweighed by the increased fire risk presented by a non-retardant TV set.

As mentioned earlier, the focus of this study was on the consequences of television fires in regard to fire safety systems and tenability limits within residential apartments. In order to properly assess the risk associated with this scenario, a more comprehensive study has to be carried out into the probability of this type of fire occurring.

This study has also revealed that there appears to be only a small amount of information available on human behaviour in heavy smoke conditions, particularly in regard to movement speed. The majority of information in the literature proved too crude to be useful in assessing short travel distances under very trying conditions. So while this study provided quantification of the available escape time for each of the tests, there is still a degree of uncertainty associated with the required escape time. In order to provide a more comprehensive answer, further work on the required escape time under conditions that realistically simulate those found in this type of scenario would be beneficial.

9. Conclusions and Recommendations

The following conclusions can be drawn from this analysis:

- The majority of television sets in New Zealand appear to have limited fire retardancy and are generally easy to ignite with a low energy naked flame.

- Untenable conditions can arise from a fire that does not produce sufficient heat to activate a fast response residential sprinkler system.

- In low heat release rate fires involving burning plastics, sufficient combustion products can accumulate in the upper layer prior to the activation of a fast response residential sprinkler head such that downdrag will result in obscuration and toxicity thresholds being exceeded in the lower part of the compartment.

- The fast response residential sprinkler system used in isolation did not achieve an equivalent level of safety to the deemed to satisfy provisions of the building code, when benchmarked against the performance of the compartment ionisation detector.

- The carbon monoxide detector was the only alternative fire safety system to achieve an equivalent level of safety to the deemed to satisfy provisions of the building code, when benchmarked against the performance of the compartment ionisation detector.

- The fast response residential sprinkler system did not provide a sufficient level of safety to allow an occupant to escape from the apartment under the fire scenario adopted for this study.

- The thermal detector did not provide a sufficient level of safety to allow an occupant to escape from the apartment under this fire scenario adopted for this study.

- Further investigation is needed to determine whether smoke detection in an adjacent space is capable of providing a sufficient level of safety to allow an occupant to escape from the apartment under the fire scenario adopted for this study.

As a result of this study, the following recommendations are offered:

- Smoke detection should not be removed from the escape route of residential accommodation until a comprehensive analysis of the probability associated with fires that can produce untenable conditions prior to sprinkler activation has been carried out. This is an integral part of the full probabilistic risk assessment that would be needed to demonstrate that reliance on the sprinkler system alone complies with the performance requirements of the building code.

- Further work should concentrate on reducing the occurrence of unwanted activations of smoke detectors. This should involve investigation into the suitability of CO detectors, as well as the use of more sophisticated smoke detectors and multi-criteria detectors. Methods of improving ventilation and extraction systems within apartments should also be considered, along with the inclusion of wall mounted hush buttons to mitigate the affects of detector activation.

- Smoke detection systems in multi-storey apartment buildings should use only local sounding (apartment of origin only) non-latching smoke detection in the apartments, and corridor detection should not be positioned near apartment doors to avoid the activation from cooking fumes escaping the apartment.

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Appendix A Glossary of Terms

Acronyms

ASET	Available Safe Escape Time
CBD	Central Business District
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COHb	Carboxyhemoglobin
deca-BDE	Decabromodiphenylether
EIRSA	Engineering, Information, Research and Strategic Analysis
FEC	Fractional Effective Concentration
FED	Fractional Effective Dose
FID	Fractional Incapacitating Dose
FLD	Fractional Lethal Dose
FR	Fire Retardant
FRS	Fire Research Station
fsd	full scale deflection
HB	Horizontal Burning
HBr	Hydrogen Bromide
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HIPS	High Impact Polystyrene
HRR	Heat Release Rate
LC_{50}	Lethal Concentration (causing death of 50 percent of animals exposed)
LCD	Liquid Crystal Display
N_2	Nitrogen
NDIR	Non-Dispersive Infrared
NFR	Non-Fire Retardant
O_2	Oxygen
OD	Optical Density
PAH	Polycyclic Aromatic Hydrocarbons

PC	Personal Computer
PFA	Perfluoro Alkoxy (Teflon)
ppm	parts per million
PPr	Polypropolyene
RMV	Respiratory Minute Volume
RSET	Required Safe Escape Time
RTI	Response Time Index
RVT	Reduced Visibility Time
Sb_2O_3	Antimony Oxide
SD	Standard Deviation
VOC	Volatile Organic Compounds

Nomenclature

Δh_c	Effective heat of combustion (kJ/kg)
A	$\left(\frac{I_o}{I}\right)$ *total* (from test measurements)
B	$\left(\frac{I_o}{I}\right)$ *sprinkler discharge*
C	Concentration (mg/l)
C_s	Light Extinction Coefficient
D	COHb concentration at incapacitation (30 percent for light activity)
D_u	Optical density per metre
F_{IN}	Fraction of an incapacitating dose of all asphyxiant gases
F_{Ico}	Fraction of an incapacitating dose of CO
F_{Icn}	Fraction of an incapacitating dose of HCN
F_{Io}	Fraction of an incapacitating dose of low-oxygen hypoxia
FLD_{irr}	Fraction of an irritant dose contributing to hypoxia
I	Intensity of the light through smoke
I_o	Intensity of the incident light

K	8.2925×10^{-4} for 25 l/min RMV (light activity)
l	Light path length (m)
LC	Lethal concentration (mg/l)
$\dot{m}$	Fuel mass loss rate (kg/s)
$\dot{Q}$	Heat release rate (kW)
t	Exposure time (min or sec)
t_{Io}	Time to incapacitation due to oxygen depletion
t_{start}	Time exposure commences
t_{end}	Time exposure ceases
VCO_2	Multiplication factor for CO_2-induced hyperventilation
W	A constant dose, specific for any effect (mg·min/l)

Appendix B UL 1626 Test Compartment

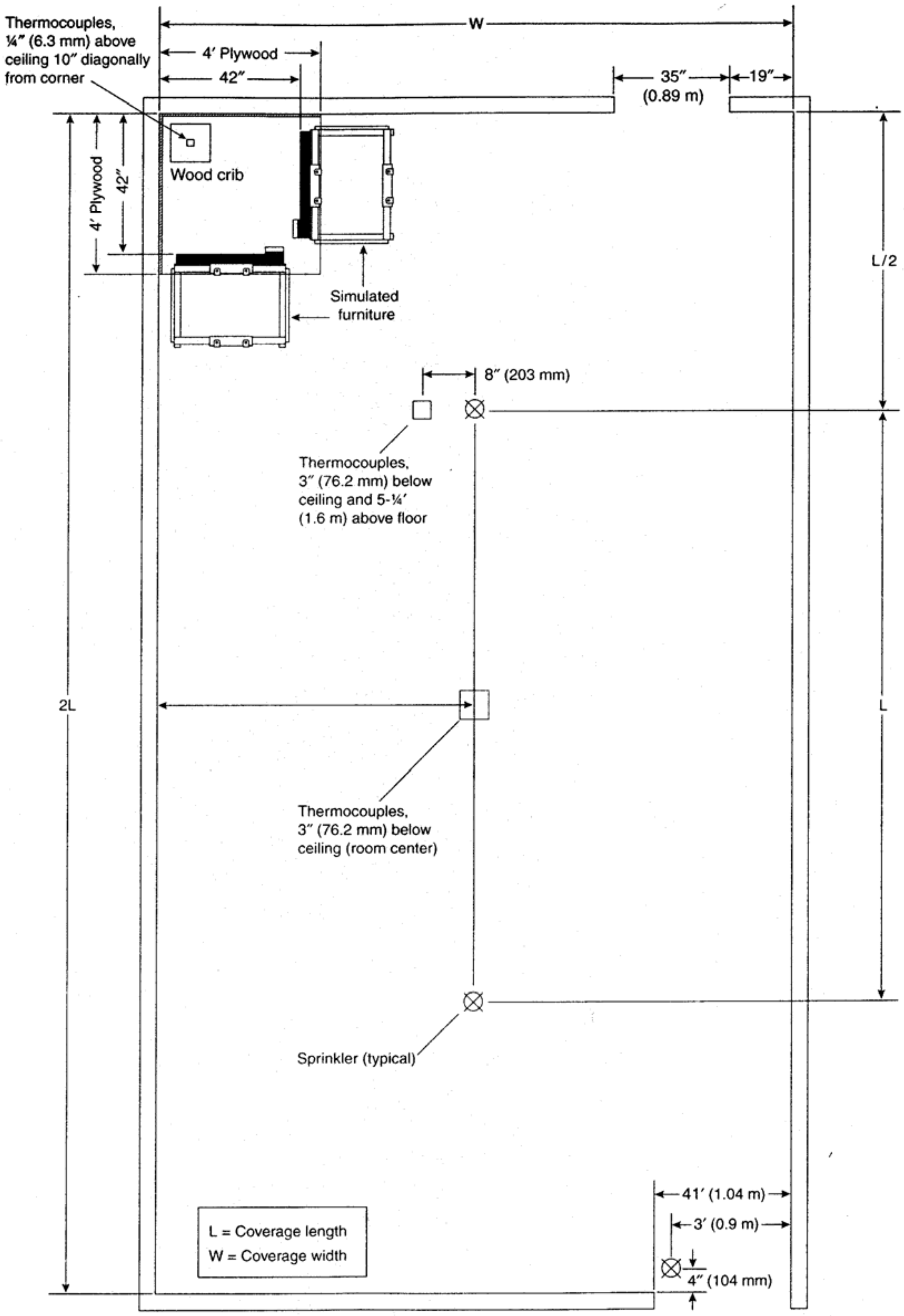

Figure B.1: UL 1626 Fire test arrangement for residential pendent sprinklers

Reproduced from Madrzykowski and Fleming [35]

Appendix C Technical Specifications

Gas Analysers

Carbon Dioxide Analyser

Manufacturer:	Autodiagnostics Limited
Model:	ADS 500 4 Gas EFI Exhaust Gas Analyser
CO_2 technology:	Non-dispersive infrared
Range:	0 – 20%
Resolution:	0.01%
Accuracy - 0 – 16%: - 16 – 20%:	± 0.4% absolute ± 1.0% absolute
Calibration:	10% CO_2
Zero check cycle (Air):	Every 30 minutes (after initial warm-up)
Data acquisition:	RS232 Link

Carbon Monoxide Analyser

Manufacturer:	The Analytical Development Company Limited
Model:	Synchronous Series 1355 Carbon Monoxide Analyser
Technology:	Non-dispersive infrared
Detector:	JMF H 2629
Range:	0 – 3% (by cell division) 0 – 10% (by gain attenuation)
Accuracy:	Better than ± 1% fsd over the whole scale
Recommended standardising mixture:	2.5% CO in N_2
Electrical output signal:	Linear 0 – 10 V

Data acquisition:	Picolog software from ADC-16 Data Logger
Supply voltage:	240 V
Supply frequency:	50 Hz

Oxygen Analyser

Manufacturer:	Servomex
Model:	540A
Technology:	Paramagnetic transducer
Local readout:	Meter
Operating range (% O_2):	0 – 25
Accuracy:	0.02% O2 or ± 1% of fsd, whichever is greater
Repeatability:	± 0.005% oxygen (electrical output)
Sample inlet temperature range (ºC):	-10 to +50
Response time (90% readout of step change at input):	6 sec. or 3 sec.
Flow rate – Cell: – Bypass:	250 ml/min max. (Air) 0.7 to 7 l/min max. (Air)
Inlet pressure:	1.4 kPag (0.2 psig) minimum 140 kPag (20 psig) maximum

Hydrogen Cyanide and Hydrogen Chloride Analyser

Manufacturer:	Gastec
Model:	Model 800 Gas Sampling Pump
Sampling capacity:	50 ml minimum (½ pump stroke) 100 ml (1 pump stroke) x n maximum

HCN	Gastec Standard detector tube No. 12M
Measuring range:	17 to 2400 ppm (50 to 800 ppm for 1 pump stroke)
Detecting limit:	1 ppm
Relative standard deviation:	10% (for 50 to 200 ppm) 5% (for 200 to 800 ppm)

HCl	Gastec Standard detector tube No. 14M
Measuring range:	10 to 1000 ppm (20 to 500 ppm for 1 pump stroke)
Detecting limit:	2.5 ppm
Relative standard deviation:	10% (for 20 to 100 ppm) 5% (for 100 to 500 ppm)

CO and O2 Gas Sampling System

Pump

Manufacturer:	Charles Austin Pumps Limited
Model:	Capex 2D
Specification No.:	480/3 VA Code 23/86

Drying Chamber

Manufacturer:	Norgren
Model:	Olympian Plus
Specification No.:	F64G – NNN – MD3
Drying agent:	Indicating blue silica gel crystals

Filter

Manufacturer:	Crossland
Element No.:	703

Data Acquisition

Data Logger

Manufacturer:	PICO Technology Limited
Model:	ADC-16 High Resolution Data Logger
No of channels:	8
Resolution:	16 bit + sign
Input range:	± 2.5 V
Overload protection:	± 30 V
Sampling rate:	1 Hz
Accuracy:	0.2%
Input impedance:	1 MΩ
Input connector:	D25 female
Output connector:	D9 male to PC serial port
Outputs:	2 (fixed ± 5 V references)
Software:	PicoLog for Windows

Terminal Block

Manufacturer:	PICO Technology Limited
Model:	ADC-16 Terminal Block

No of channels used:	3
Resistor A (R_a):	75,000 Ω
Resistor B (R_b):	25,000 Ω

Thermocouple Logger

Manufacturer:	PICO Technology Limited
Model:	TC-08 Thermocouple to PC Data Logger
No of channels:	8
Accuracy:	The sum of ± 0.3% and 0.5°C
Overload protection:	± 10 V
Conversion time:	200 µs for cold junction compensation + 200 µs per active channel
Input connectors:	Miniature thermocouple
Max common mode voltage:	± 5 V
Output connector:	D9 female to serial port
Dimensions:	85 x 145 x 25 mm
Software:	PicoLog for Windows

Visual Obscuration

Laser Optical Density Meter

Transmitter

Wavelength:	650 nm
Supply voltage:	9 V

Receiver

Manufacturer:	Silonex
Model:	SLD-70BG2 Infrared Rejection Filter Planar Photodiode
Operating mode:	Photovoltaic
Spectral range:	400 – 700 nm
Maximum sensitivity:	550 nm
Electric output signal:	Linear 0 – 9 V
Supply voltage:	12 V

Mass Loss

Electronic Scales and Indicator

Manufacturer:	Mettler Toledo
Model:	Spider SW
Capacity:	150 kg
Resolution:	0.005 kg
Zero setting range:	1.2% of total load cell capacity
Auto zero range:	0.16% of the stated scale's weighing capacity
Start-up zero range:	-1.4% to +12.6% of the total load cell capacity
Maximum preload:	70% of the nominal load of the stated scale weighing capacity
Linearity:	0.033% of the total load cell capacity
Data acquisition:	RS-232C bi-directional (9600 8-N-1)
Handshake:	XON/XOFF
Maximum data rate:	20 weigh values per second

Sprinkler System

Sprinkler Heads

Manufacturer:	Tyco Fire and Building Products
Model:	Series LFII Residential Pendent Sprinklers
Model identification no.:	SIN TY2234
K-factor:	4.9 GPM/psi^{½} (70.6 l/min/bar^{½})
Temperature rating:	68°C
Bulb:	3 mm diameter, glass
Maximum working pressure:	1210 kPa

Design specifications
(Horizontal ceiling)

Maximum coverage area:	4.3 m x 4.3 m
Maximum spacing:	4.3 m
Minimum flow:	49.2 l/min
Residual pressure:	48 kPa

Fire Detectors

Ionisation Detector

Manufacturer:	Apollo Fire Detectors Limited
Model:	XP95 Ionisation Detector
Part number:	55000-500
Radioactive isotope:	Americium 241
Sampling frequency:	Continuous
Supply voltage:	17 to 28 V dc

Operating temperature:	-20°C to +70°C
Clean air analogue value:	25 ±7 counts
Alarm level analogue value:	55 (EN54 y value of 0.7)
Sensitivity:	Nominal threshold y value of 0.7 to EN54 Pt 7 1984
Humidity:	0% to 95% relative humidity
Wind speed:	10 m/s maximum
Data acquisition:	Proprietary software using Apollo communications protocol

Optical Detector

Manufacturer:	Apollo Fire Detectors Limited
Model:	XP95 Optical Smoke Detector
Part number:	55000-600
Sensor:	Silicon PIN photo-diode
Emitter:	GaAs Infra-red light emitting diode
Sampling frequency:	1 second
Supply voltage:	17 to 28 V dc
Operating temperature:	-20°C to +60°C
Clean air analogue value:	25 ±7 counts
Alarm level analogue value:	55
Sensitivity:	Nominal threshold of 2.4% light grey smoke obscuration per metre
Humidity:	0% to 95% relative humidity
Wind speed:	Unaffected by wind
Data acquisition:	Proprietary software using Apollo communications protocol

Thermal Detector

Manufacturer:	Apollo Fire Detectors Limited
Model:	XP95 Temperature detector (Standard)
Part number:	55000-400
Sensor:	Single NTC thermistor
Sampling frequency:	Continuous
Supply voltage:	17 to 28 V dc
Operating temperature:	-20°C to +70°C
Analogue value at 25°C:	25 ±5 counts
Alarm level analogue value at 55°C:	55
Sensitivity:	25°C to 90°C: 1°C/count -20°C returns 8 counts
Humidity:	0% to 95% relative humidity
Wind speed:	Unaffected by wind in fixed temperature use
Data acquisition:	Proprietary software using Apollo communications protocol

Carbon Monoxide Detector

Manufacturer:	Apollo Fire Detectors Limited
Model:	Discovery Carbon Monoxide Detector
Part number:	58000-300
Cell life:	7 years (assuming regular checks are satisfactory)
Sampling frequency:	1 per second
Remote output characteristics:	Connects to positive line through 4.5Ω (5mA maximum)

Supply voltage:	17 – 28 V dc
Operating temperature:	Continuous: 0°C to +50°C Transient: -40°C to +60°C
Clean air analogue value:	25 ±2 counts
Alarm level analogue value:	55
Sensitivity (temperature):	Less than 15% change in sensitivity over rated range
Humidity:	15% to 90% relative humidity
Wind speed:	Unaffected by wind
Data acquisition:	Proprietary software using Apollo communications protocol

Appendix D Television Specifications

Test 0

Make:	Philips Nicam Digital Stereo
Model:	25GR6771/79 R
Power supply:	230 V ~ 50 Hz
Output:	90 W
Serial No.:	SV019135 101569
Mass:	28.595 kg

Test 1

Make:	Mitsubishi
Model:	CT-25AM2(NZ)
Power supply:	230 V ~ 50 Hz
Output:	125 W
Serial No.:	25AM 206889 775A022A7
Mass:	29.88 kg

Test 2

Make:	Panasonic
Model:	CN218RVQ
Power supply:	230 V ~ 50 Hz
Output:	111 W
Distributor:	Fisher and Paykel
Mass:	24.28 kg

Test 3

Make:	Sony Trinitron Color TV
Model:	KV-21VX1MT
Power supply:	~ 110 V – 127 V – 220 V – 240 V 50 Hz / 60 Hz
Output:	135 W
Serial No.:	2004390
Mass:	24.715 kg

Test 4

Make:	Philips
Model:	20CT636/79 R
Power supply:	230 V ~ 50 Hz
Output:	60 W
Serial No.:	SV 00 8910 101536
Mass:	20.900 kg

Test 5

Make:	Toshiba Colour TV
Model:	2132DB
Power supply:	220 - 240 V ~ 50 Hz
Output:	103 W
Serial No.:	SV 40150790
Mass:	19.420 kg

Test 6

Make:	Panasonic Colour TV Matsushita Electric Industrial Co. Ltd
Model:	TC-20L32
Power supply:	230 V ~ 50 Hz
Output:	98 W
Serial No.:	MA3610244
Distributor:	Fisher and Paykel
Manufactured in:	Malaysia
Mass:	21.185 kg

Test 7

Make:	Sanyo
Model:	C25ZG51
Service Ref. No.:	C25ZG51-01
Chassis series:	AA1-A25
Power supply:	AC 230 V ~ 50 Hz
Output:	105 W
Serial No.:	27705857 1AA6P4SO483-A A-E8EV
Mass:	25.97 kg

Test 8

Make:	Sony Trinitron Color TV
Model:	KV-T25SF11
Power supply:	~ 110 – 240 V 50/60 Hz
Output:	148 W
Serial No.:	1000172
Manufactured in:	Malaysia
Mass:	30.385 kg

Test 9

Make:	Goldstar Cinemaster 23 System
Model:	CF-20A74
Power supply:	100 – 270 V ~ 50/60 Hz
Output:	80 W
Serial No.:	2074050108219
Manufactured in:	Jordan
Mass:	18.415 kg

Test 10

Make:	Philips Powervision
Model:	21GR1369/79 R UHF + VHF
Power supply:	230 V ~ 50 Hz
Output:	60 W
Serial No.:	SVO 39228 100252
Mass:	22.210 kg

Test 11

Make:	Toshiba Colour TV
Model:	207R9A
Power supply:	240 – 250 V ~ 50 Hz
Output:	60 W
Serial No.:	15623152
Manufactured in:	Singapore
Mass:	17.755 kg

Test 12

Make:	Sony Trinitron Colour TV
Model:	KV-2153 8N
Power supply:	~ 200 – 240 V 50 Hz
Output:	130 W
Serial No.:	1000881
Manufactured in:	Malaysia
Mass:	24.065 kg

Test 13

Make:	Mitsubishi
Model:	CT-2148NZM
Power supply:	~ 230 V 50 Hz
Output:	88 W
Serial No.:	NZ214802849
Mass:	22.335 kg

Test 14

Make:	Transonic 20” Color Television
Model:	CTV-5144
Power supply:	240 V ~ 50 Hz
Output:	75 W
Serial No.:	93101934
Manufactured in:	China
	08 10
Mass:	19.395 kg

Test 15

Make:	Sanyo
Model:	CZP2141TXA-00
Chassis series:	A3-B21
Power supply:	AC 220 - 240 ~ 50 Hz
Output:	76 W
Serial No.:	27203410
Manufactured in:	Singapore
Mass:	21.220 kg

Test 16

Make:	Philips
Model:	20GR1250/79 R
Power supply:	230 V ~ 50 Hz
Output:	55 W
Serial No.:	SV 00 9023 103577
Mass:	19.39 kg

Test 17

Make:	Sanyo
Model:	C29ZK80TX-51
Chassis series:	AA1-A29
Power supply:	AC 220 - 240 ~ 50 Hz
Output:	125 W
Manufactured in:	Indonesia
Mass:	37.025 kg

Test 18

Make:	Transonic 20” (51 cm) Color Television
Model:	CTV-5144
Power supply:	240 V ~ 50 Hz
Output:	75 W
Serial No.:	93101442
Manufactured in:	China
	08 10
Mass:	19.115 kg

Test 19

Make:	Samsung
Model:	CB-681 3WT
Power supply:	AC 230 V ~ 50 Hz
Output:	125 W
Serial No.:	323732BB200109
Manufactured in:	Korea
Mass:	32.33 kg

Test 20

Make:	Sony Trinitron Color TV
Model:	KV-T25SF81
Power supply:	~ 110 – 240 V 50/60 Hz
Output:	148 W
Serial No.:	1001193
Manufactured in:	Malaysia
Mass:	30.400 kg

Test 21

Make:	Transonic 29” High Resolution Color TV
Model:	GT-8828
Power supply:	AC ~ 240 V / 50 Hz
Output:	120 W
Mass:	31.585 kg

Appendix E   Fire Safety Systems Response

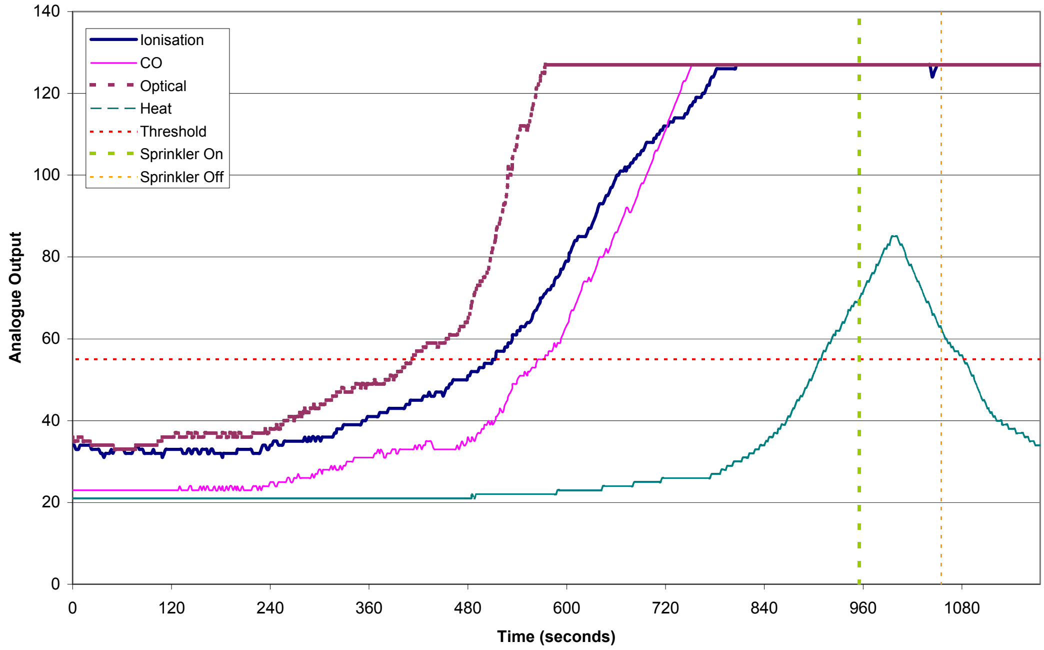

Figure E.1: Test 1 - Compartment fire safety system response

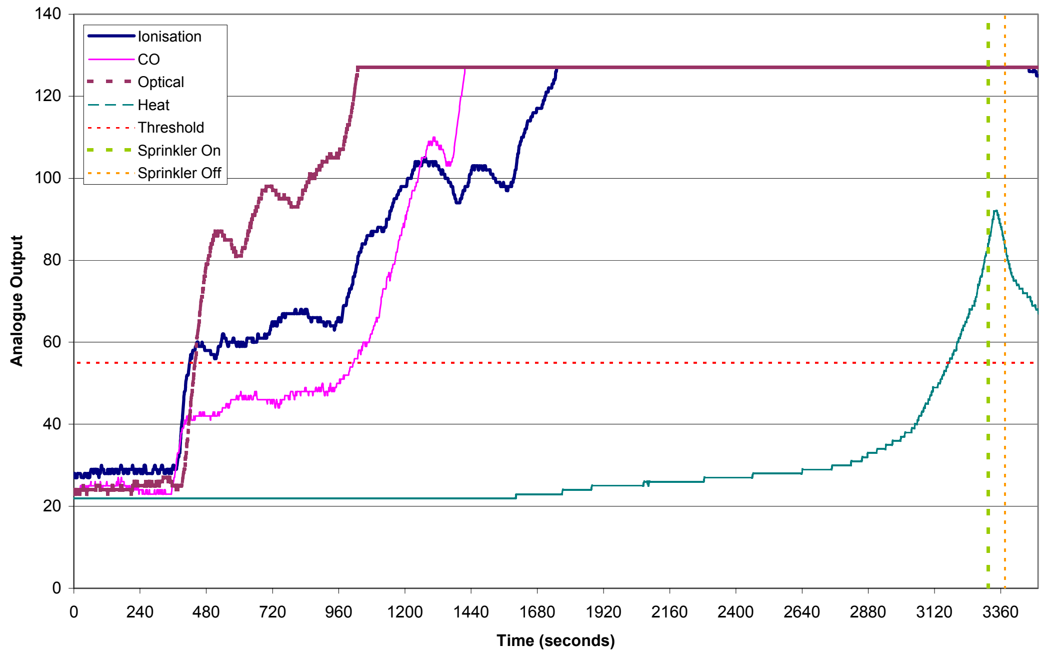

Figure E.2: Test 2 - Compartment fire safety system response

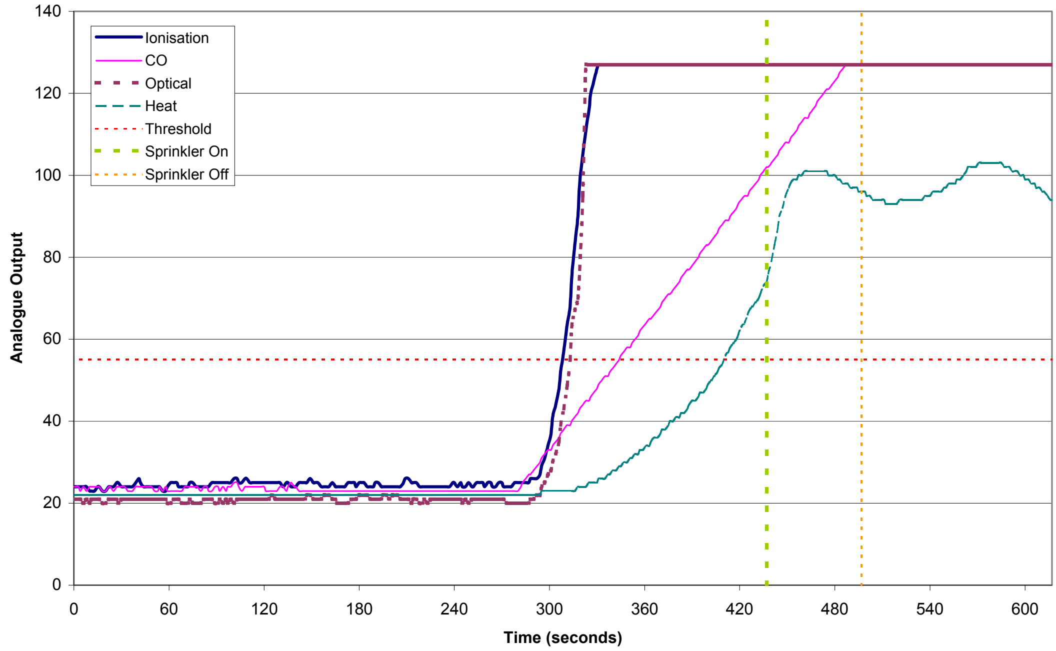

Figure E.3: Test 3 - Compartment fire safety system response

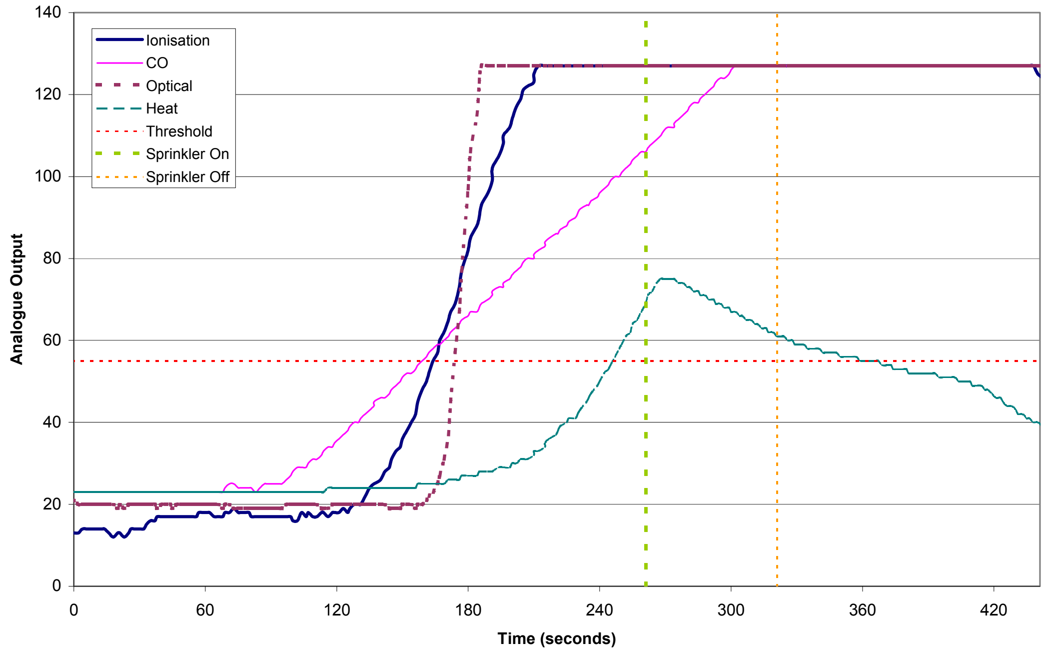

Figure E.4: Test 4 - Compartment fire safety system response

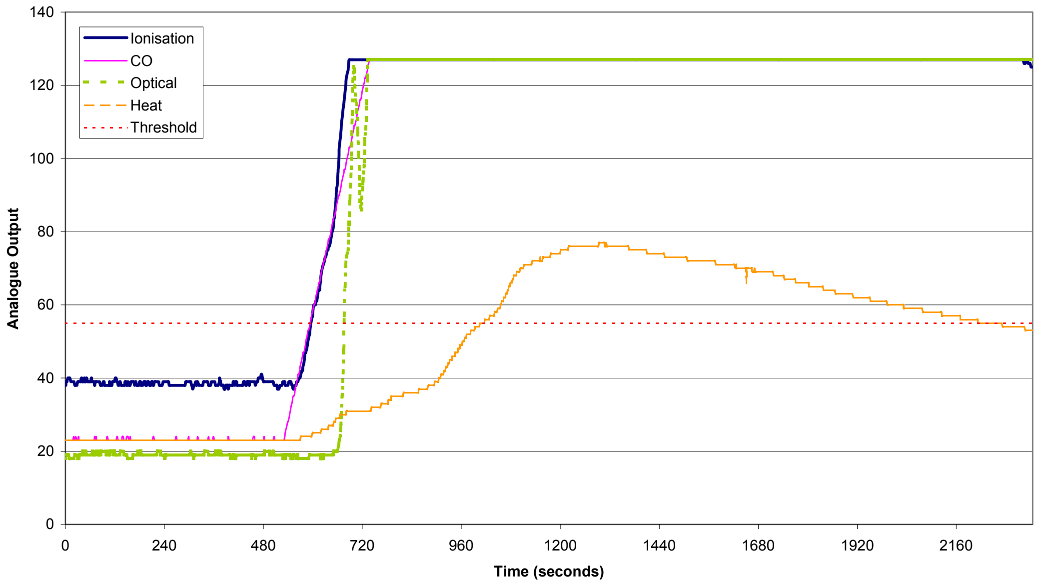

Figure E.5: Test 5 - Compartment fire safety system response

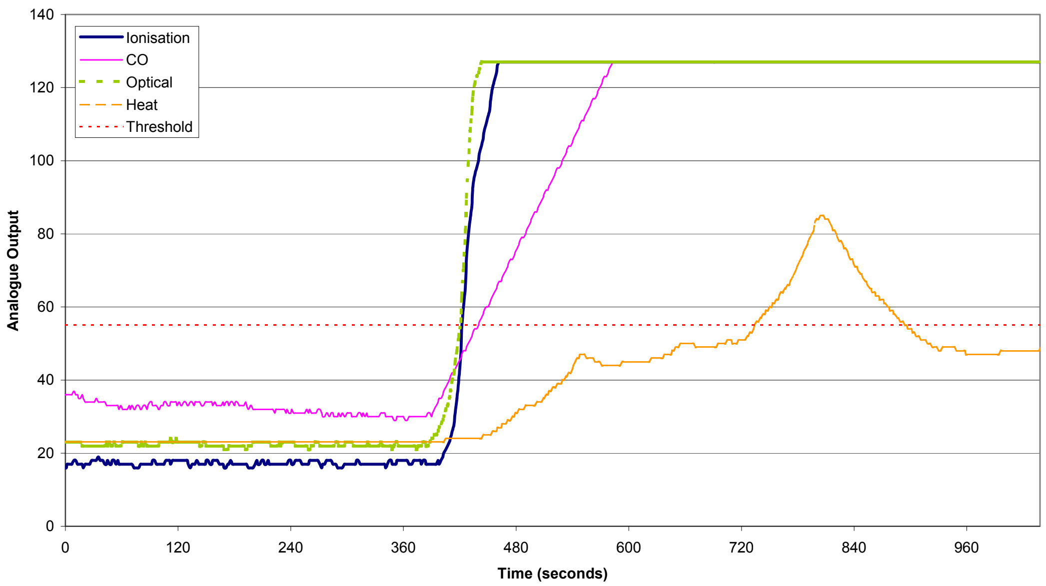

Figure E.6: Test 6 - Compartment fire safety system response

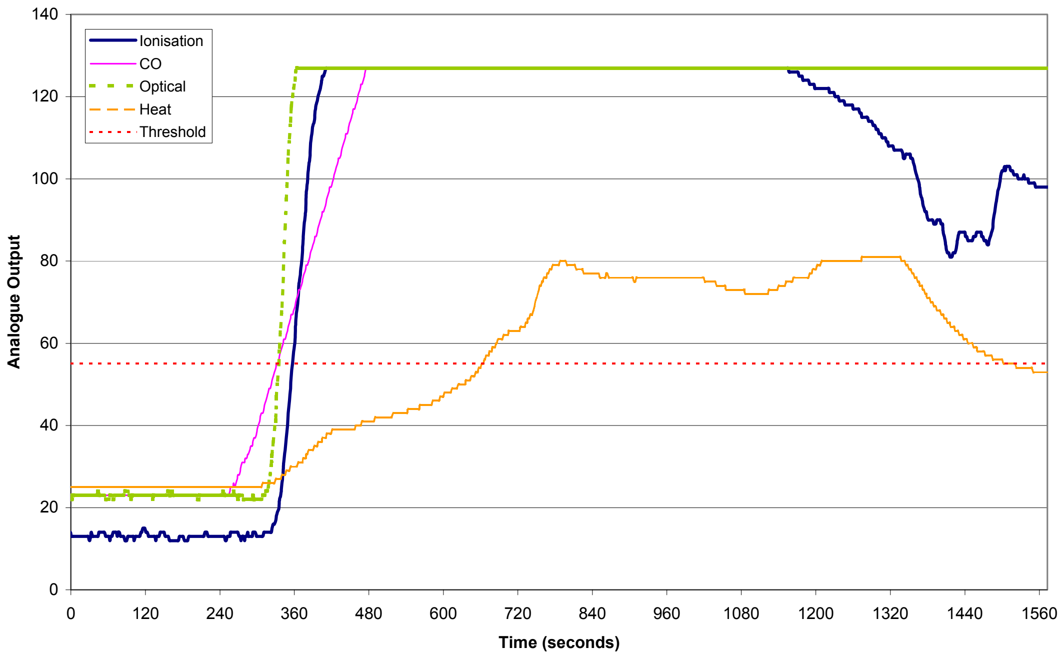

Figure E.7: Test 7 - Compartment fire safety system response

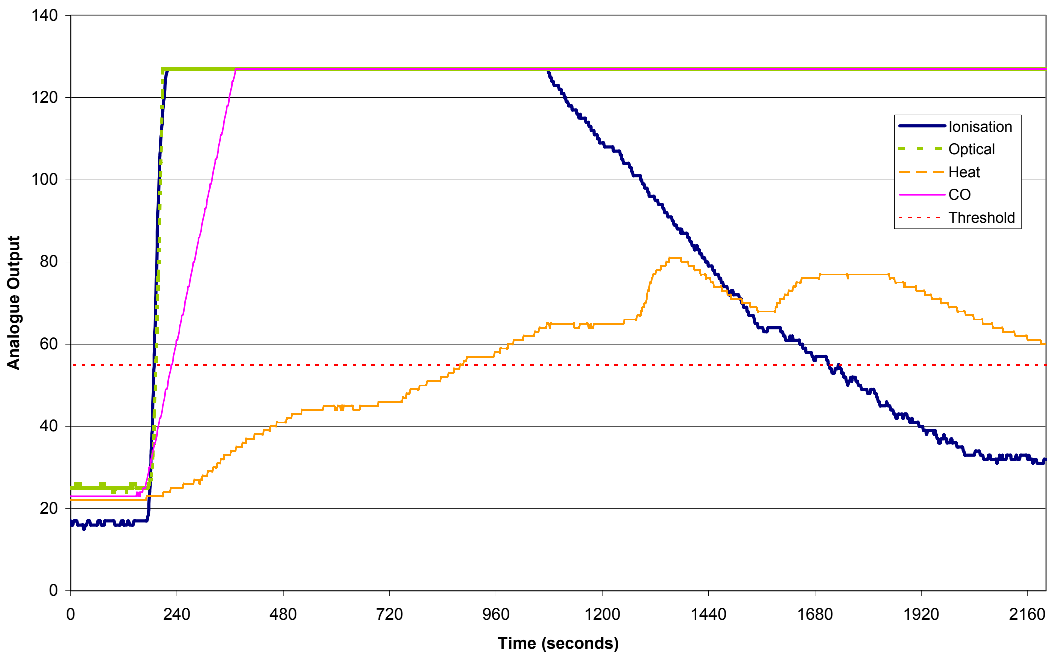

Figure E.8: Test 8 - Compartment fire safety system response

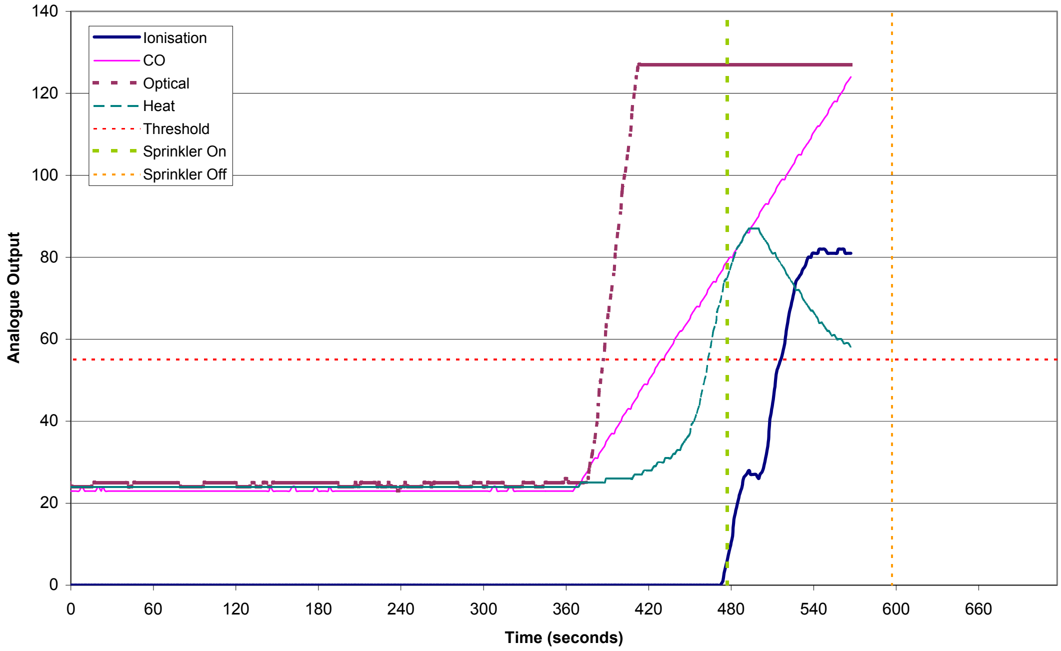

Figure E.9: Test 9 - Compartment fire safety system response

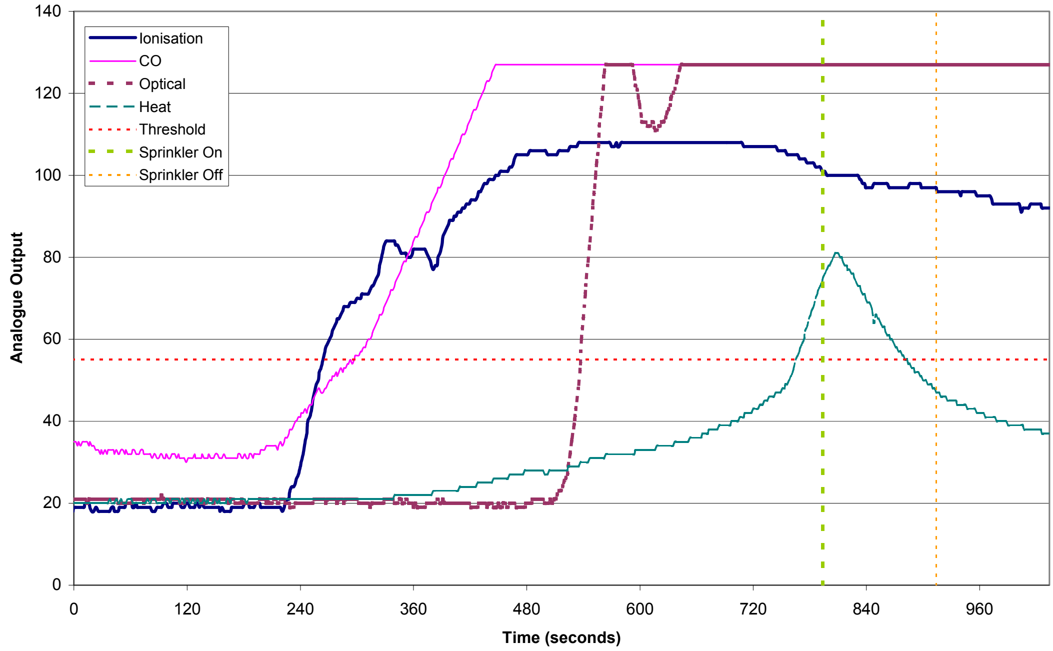

Figure E.10: Test 13 - Compartment fire safety system response

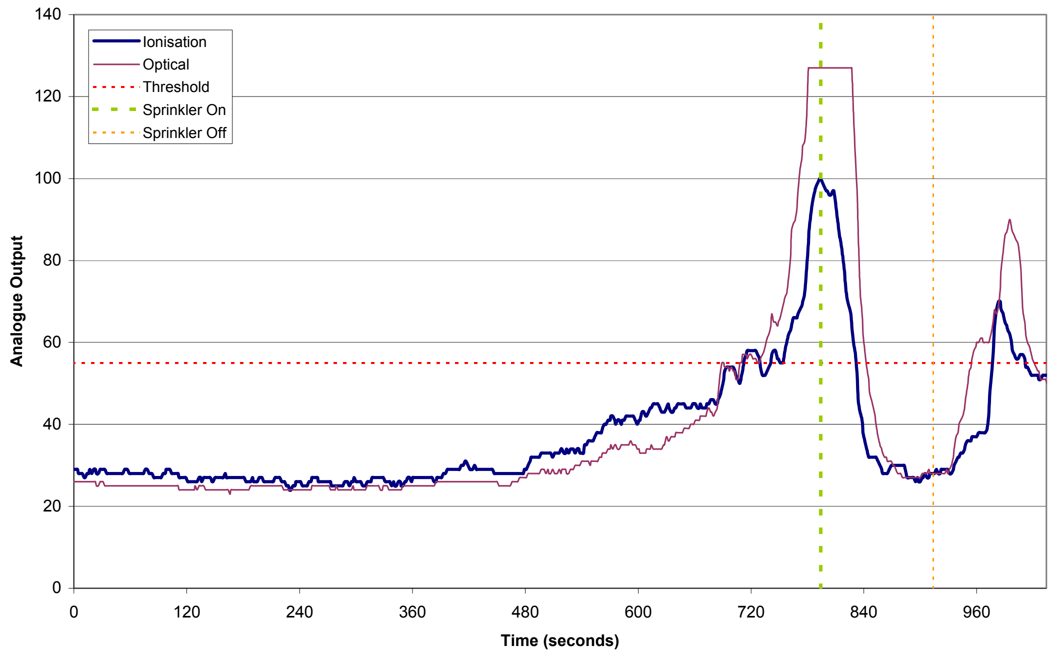

Figure E.11: Test 13 - Lobby fire safety system response

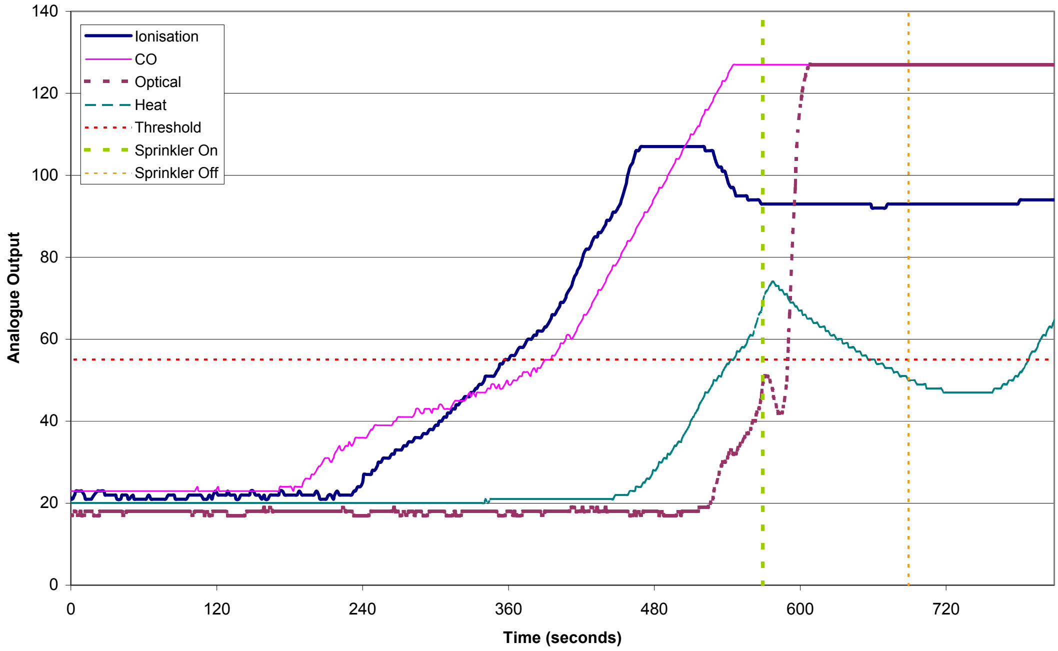

Figure E.12: Test 14 - Compartment fire safety system response

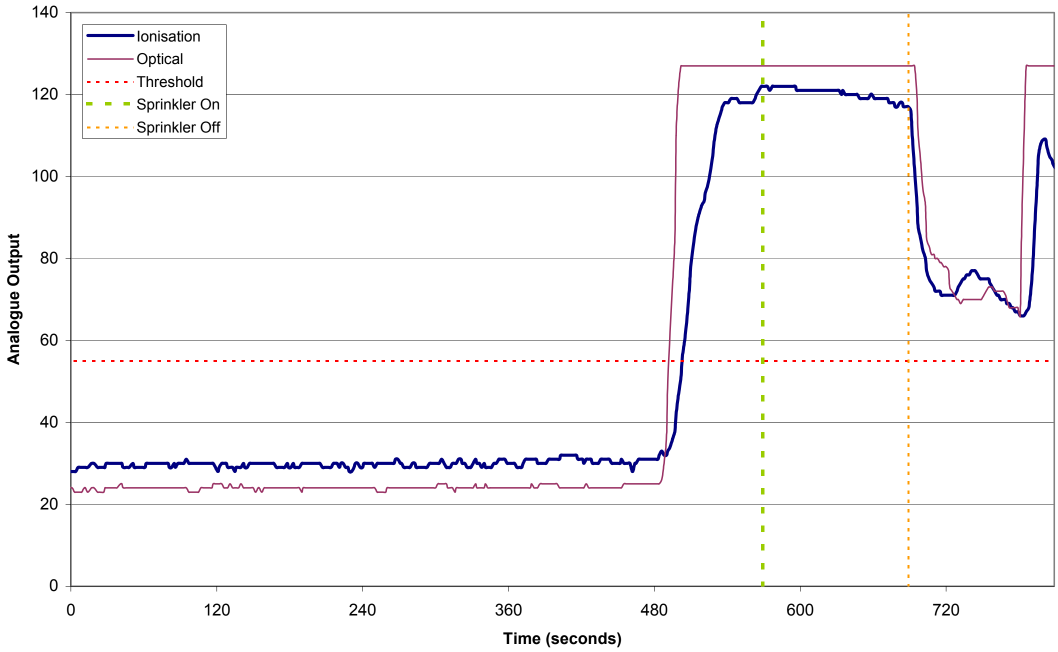

Figure E.13: Test 14 - Lobby fire safety system response

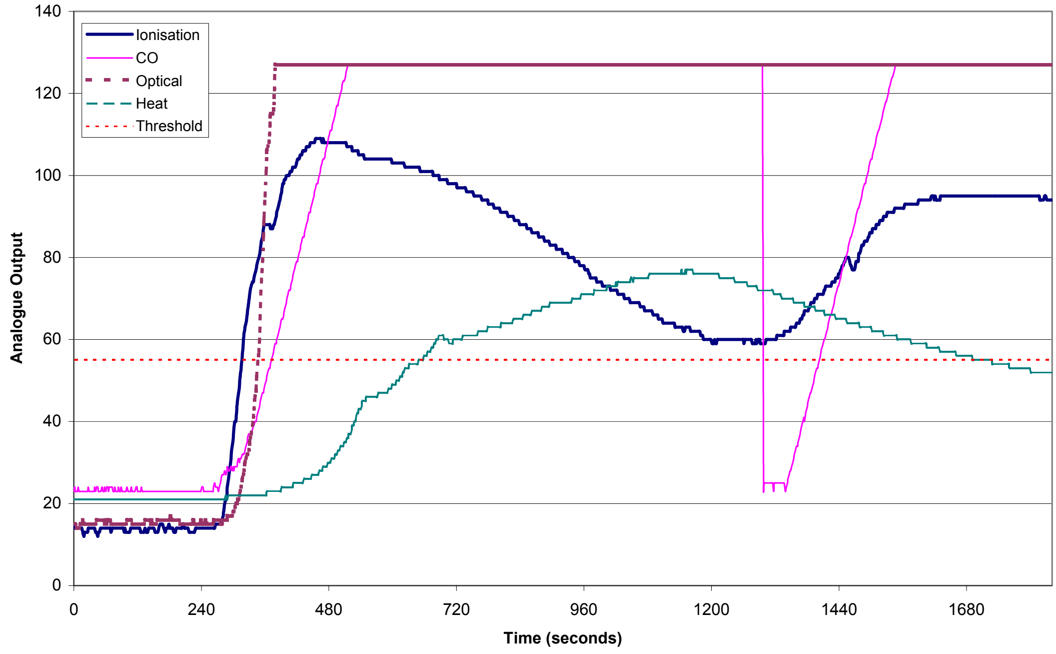

Figure E.14: Test 15 - Compartment fire safety system response

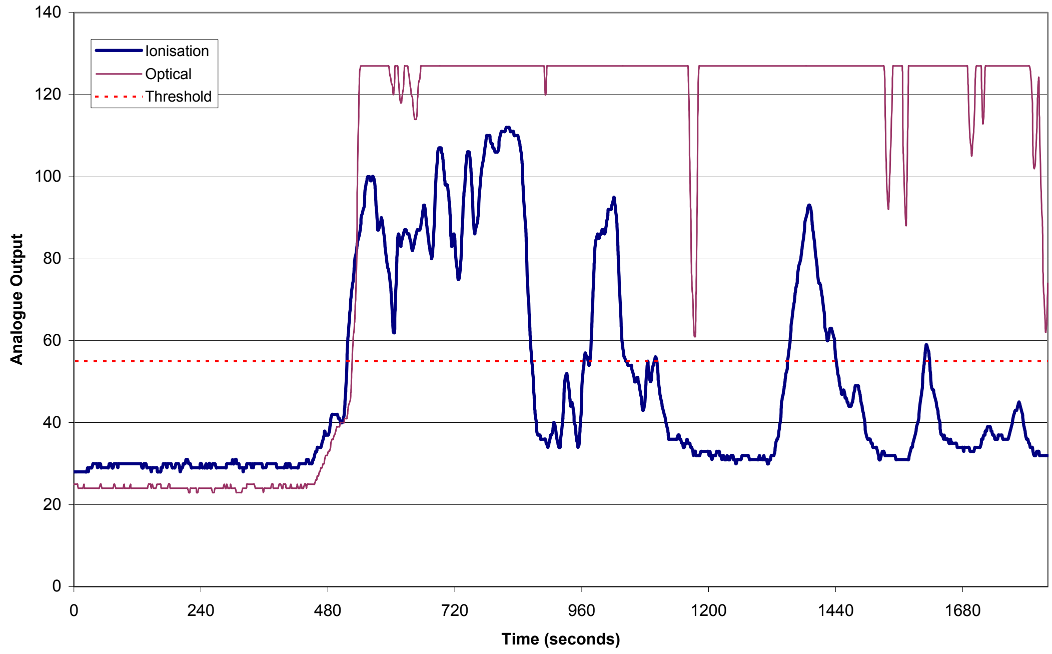

Figure E.15: Test 15 - Lobby fire safety system response

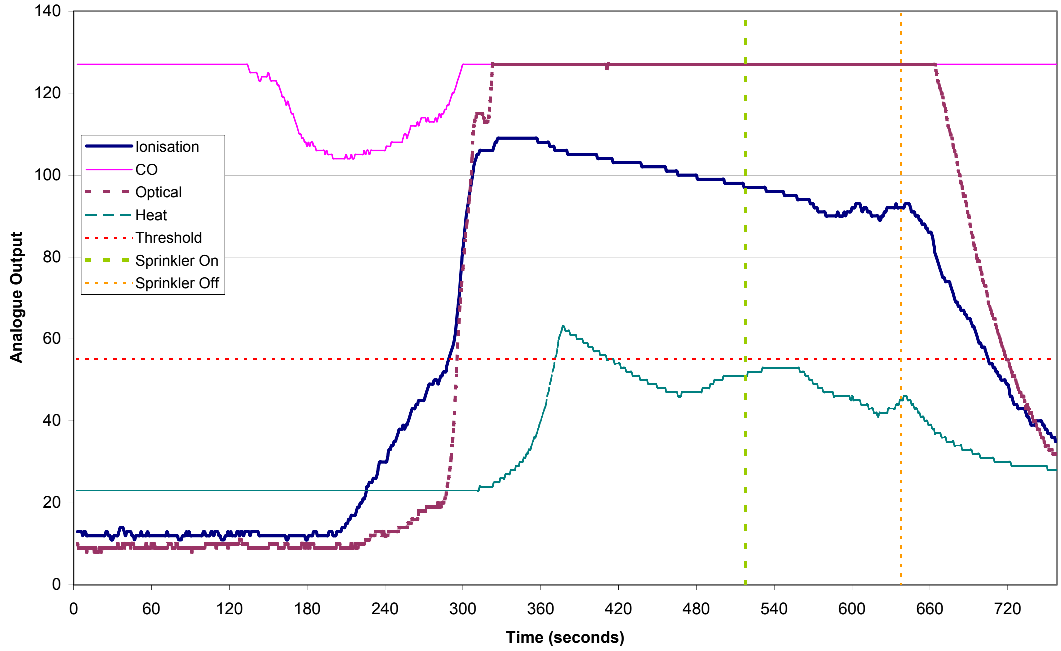

Figure E.16: Test 16 - Compartment fire safety system response

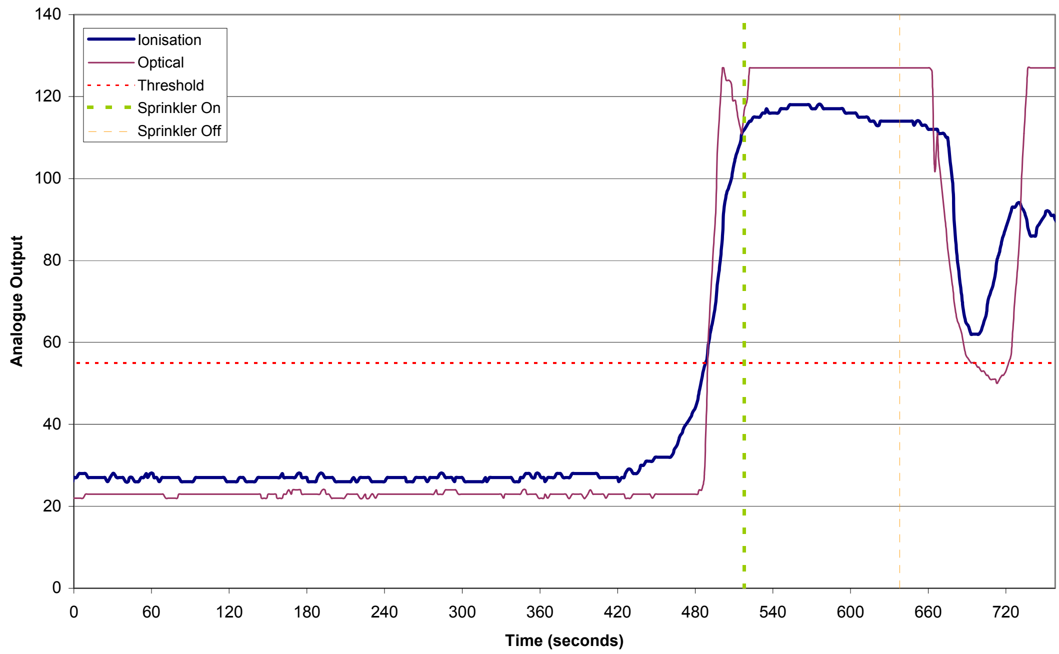

Figure E.17: Test 16 - Lobby fire safety system response

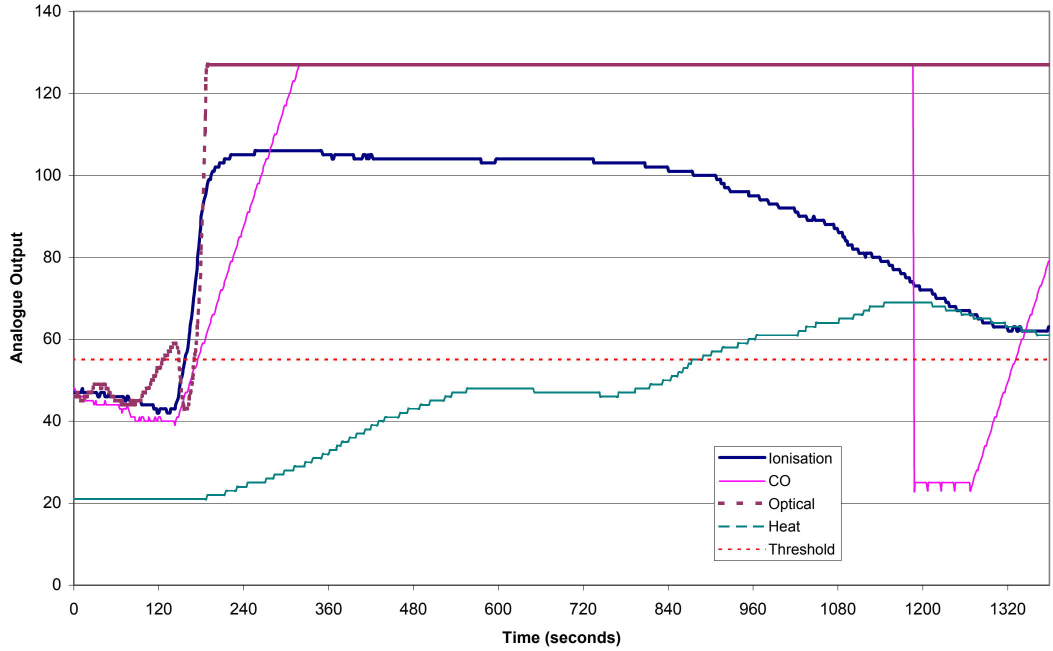

Figure E.18: Test 17 - Compartment fire safety system response

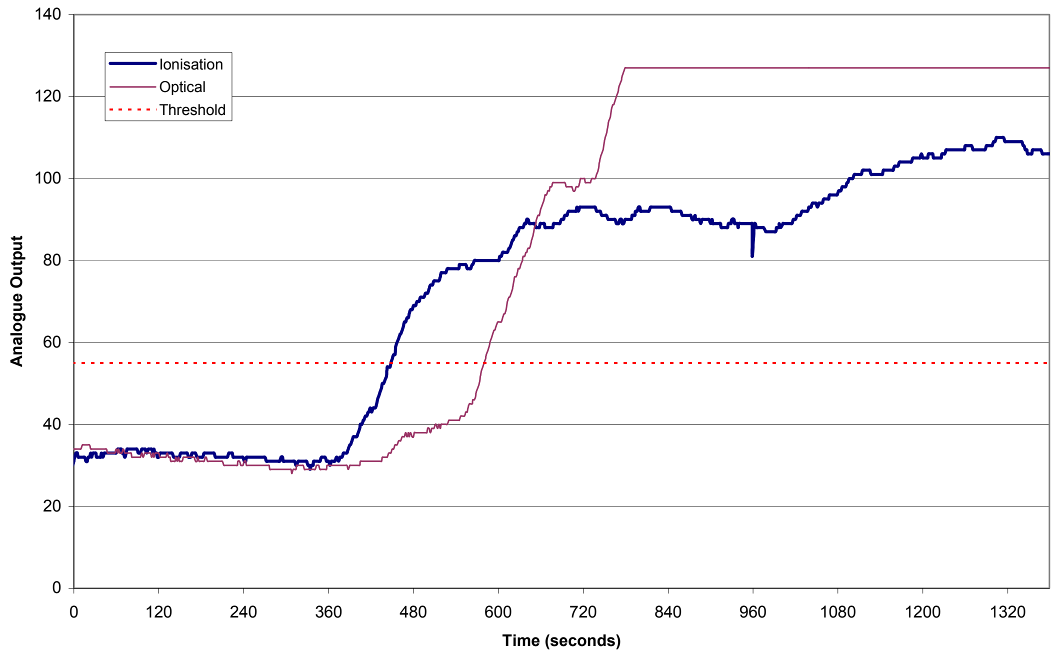

Figure E.19: Test 17 - Lobby fire safety system response

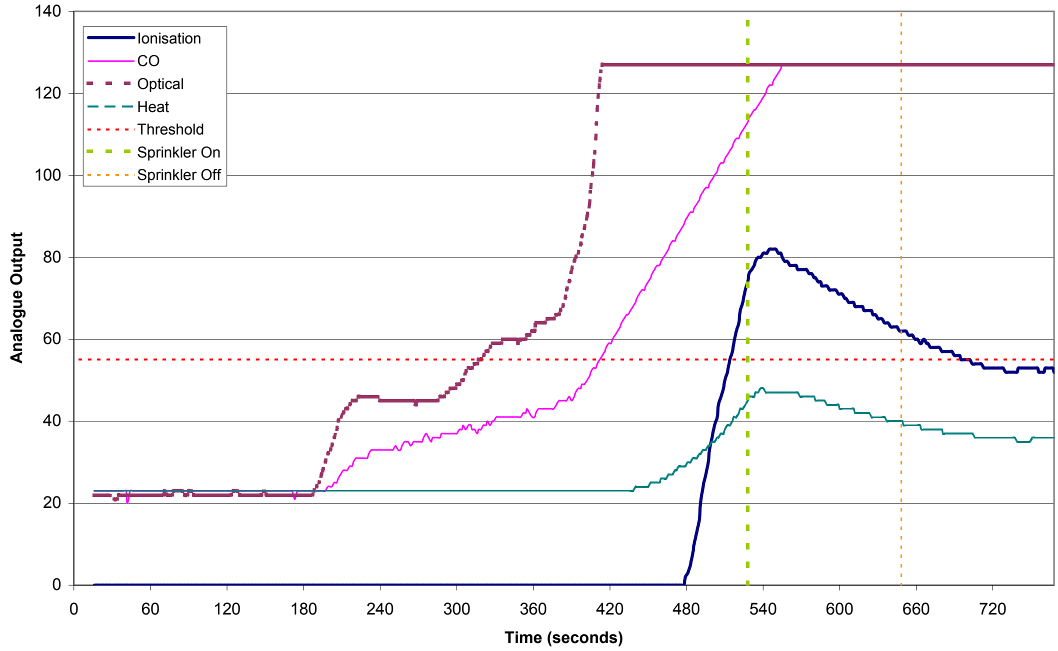

Figure E.20: Test 18 - Compartment fire safety system response

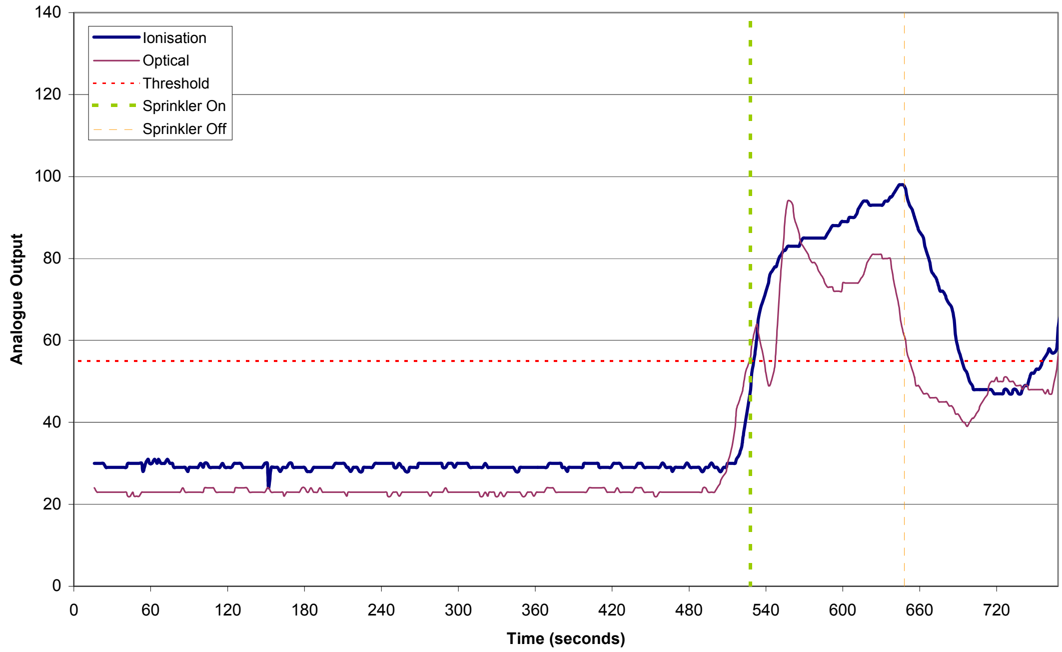

Figure E.21: Test 18 - Lobby fire safety system response

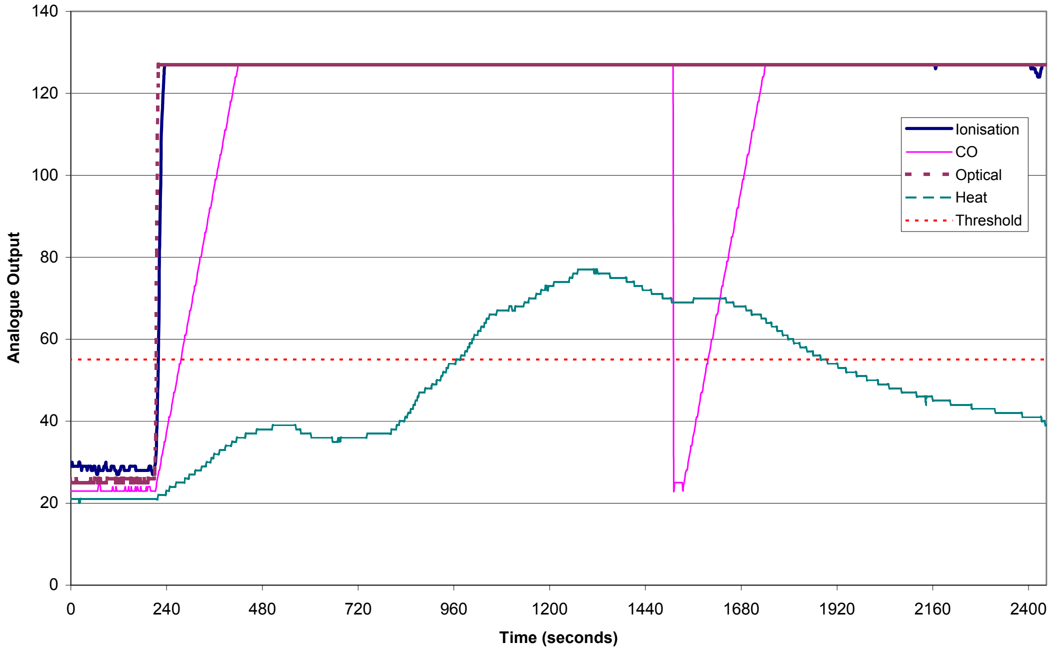

Figure E.22: Test 20 - Compartment fire safety system response

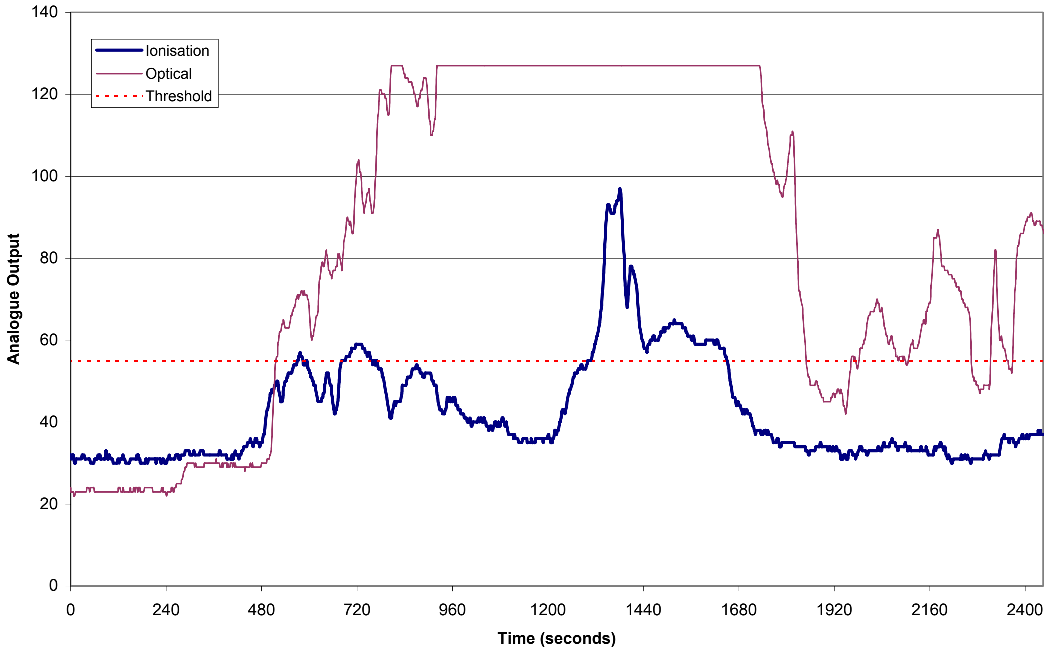

Figure E.23: Test 20 - Lobby fire safety system response

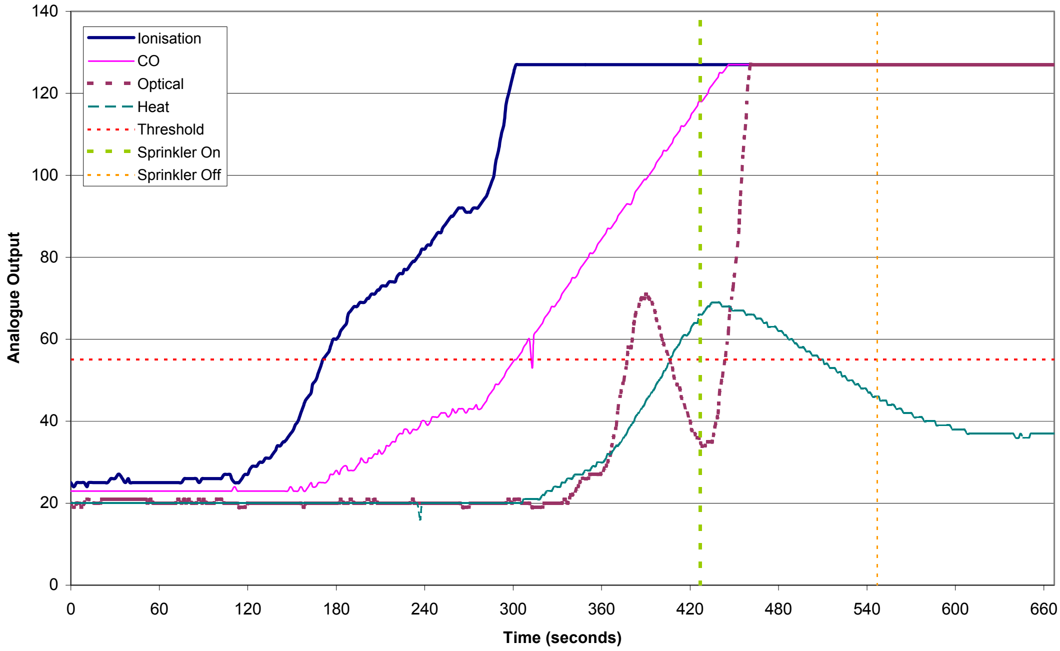

Figure E.24: Test 21 - Compartment fire safety system response

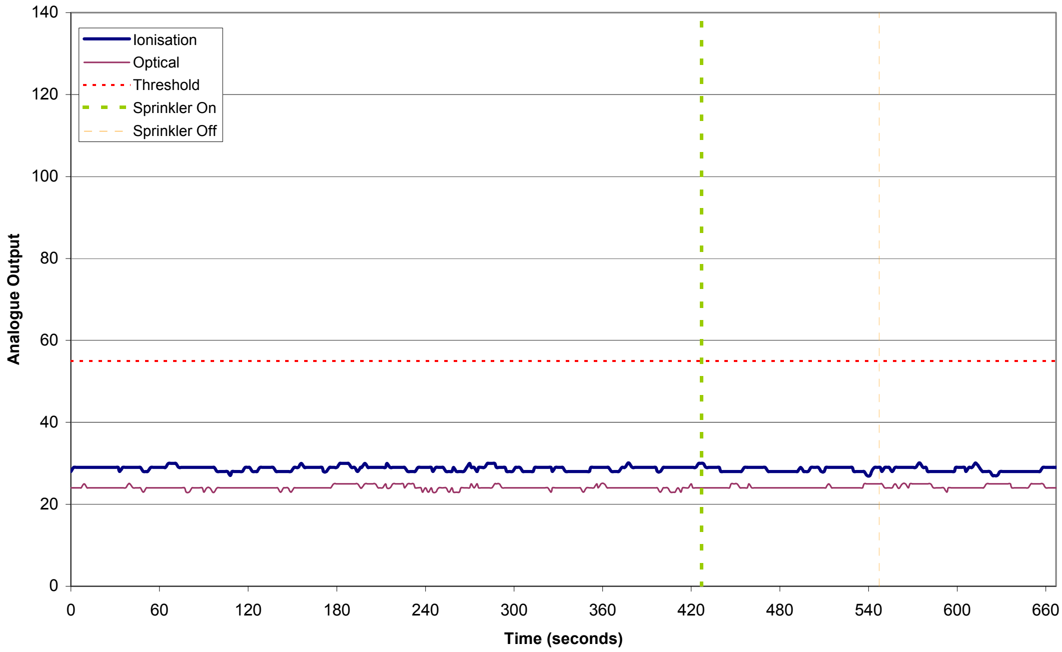

Figure E.25: Test 21 - Lobby fire safety system response

Appendix F Systems Activation Distribution

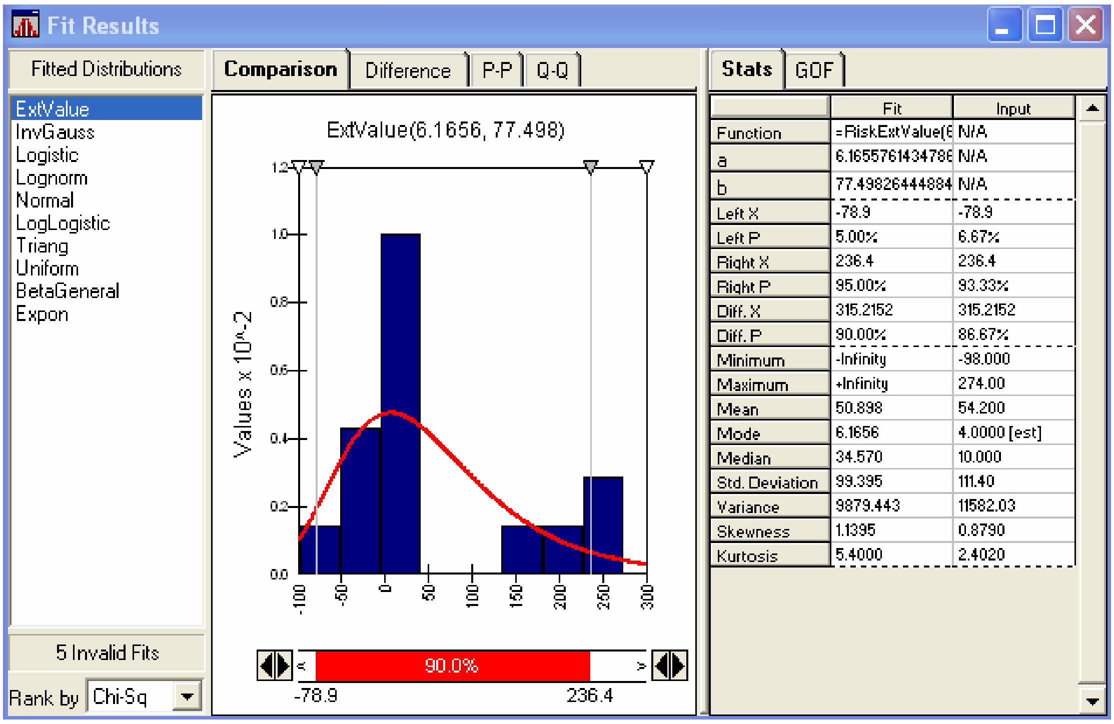

Figure F.1: Difference in activation times between optical and ion detectors

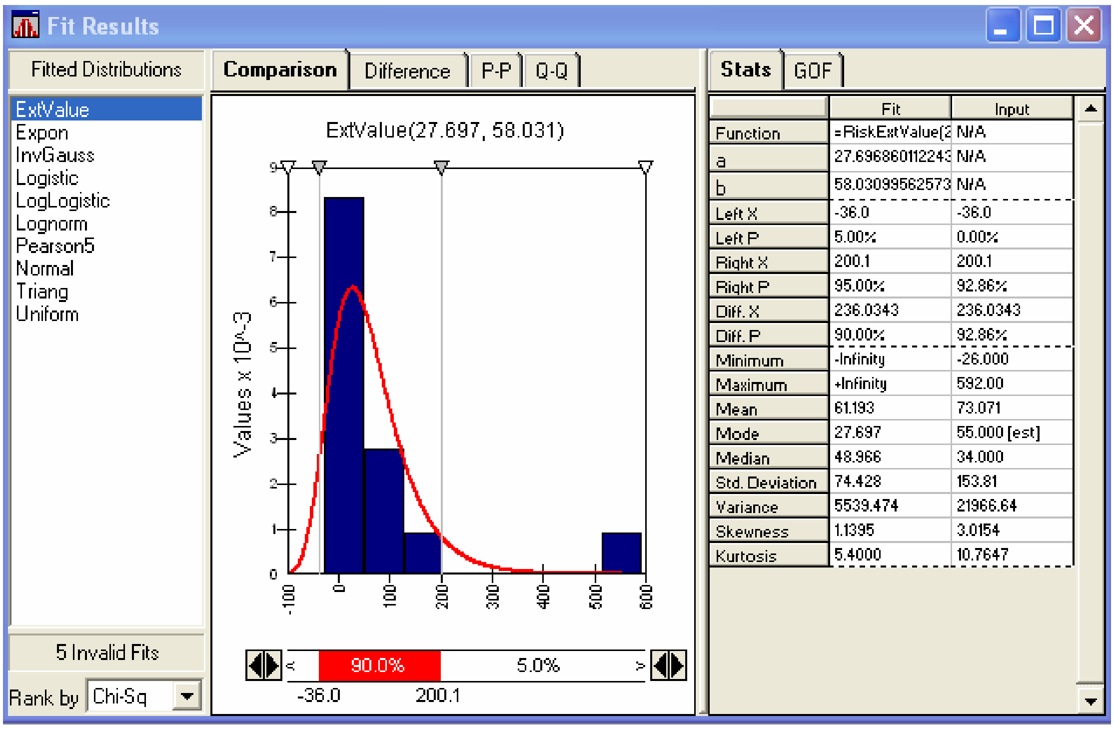

Figure F.2: Difference in activation times between CO and ionisation detectors

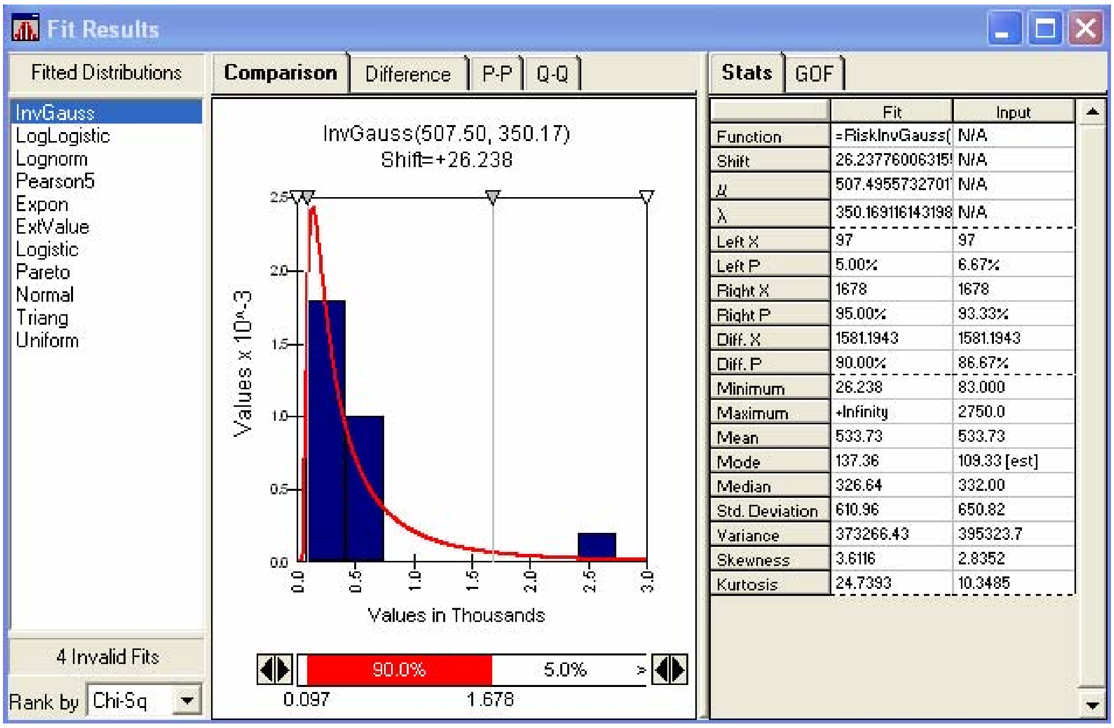

Figure F.3: Difference in activation times between thermal and ion detectors

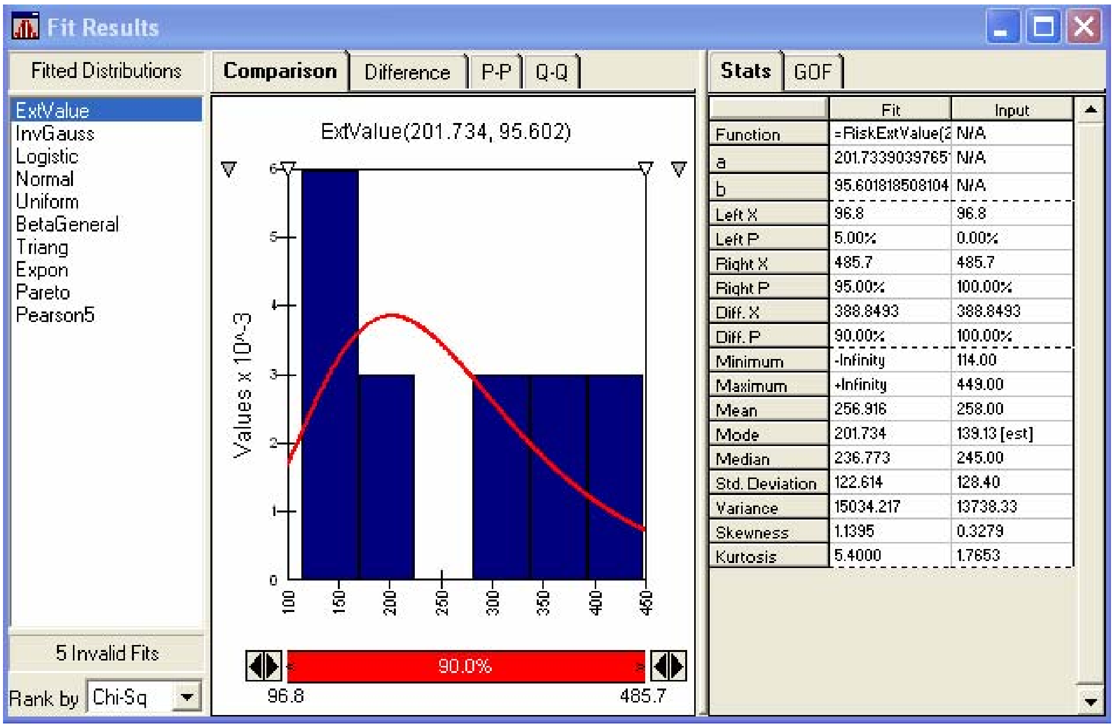

Figure F.4: Difference in activation times between lobby ion and ion detectors

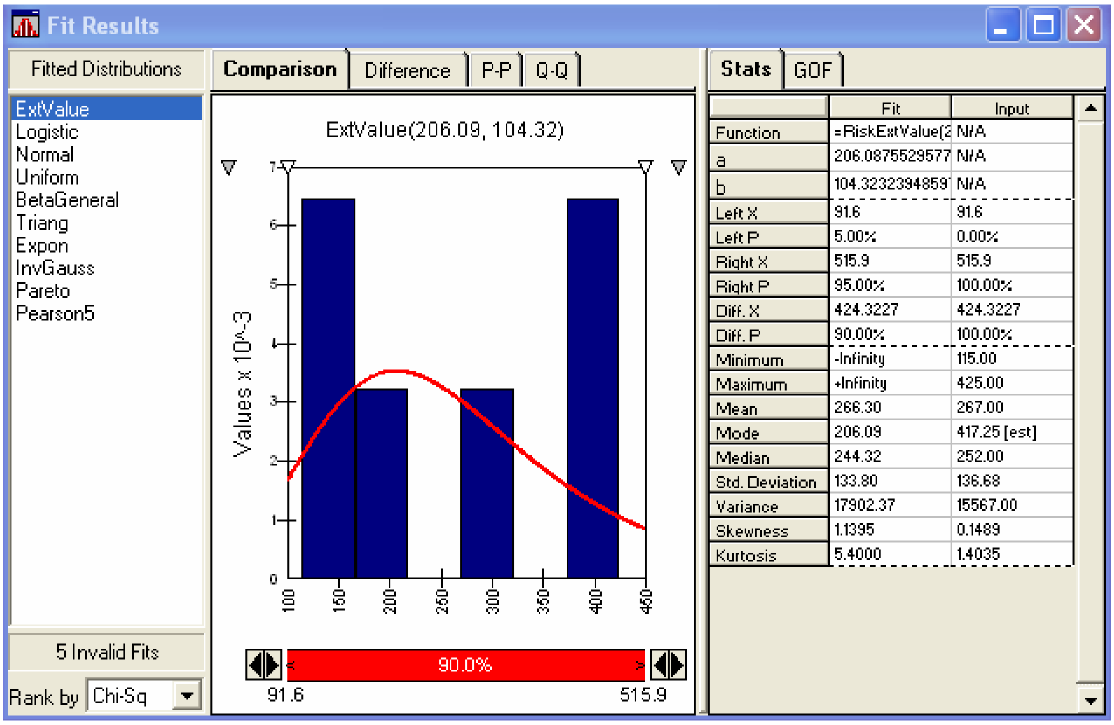

Figure F.5: Difference in activation times between lobby opt and ion detectors

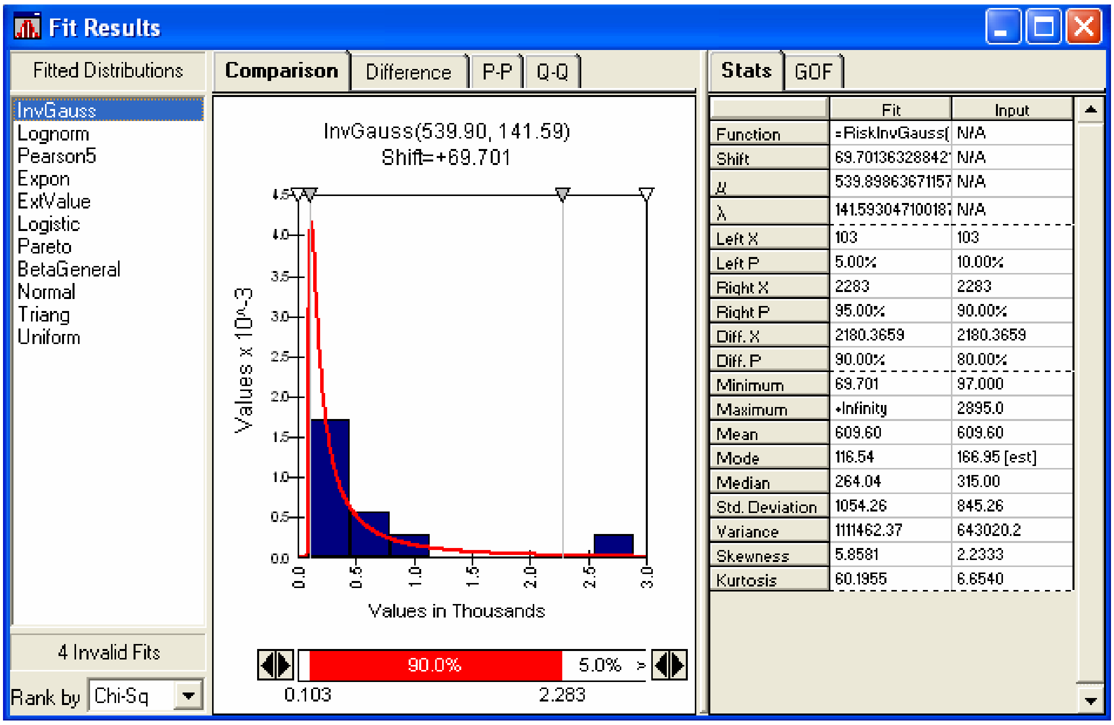

Figure F.6: Difference in activation times between sprinkler and ion detector

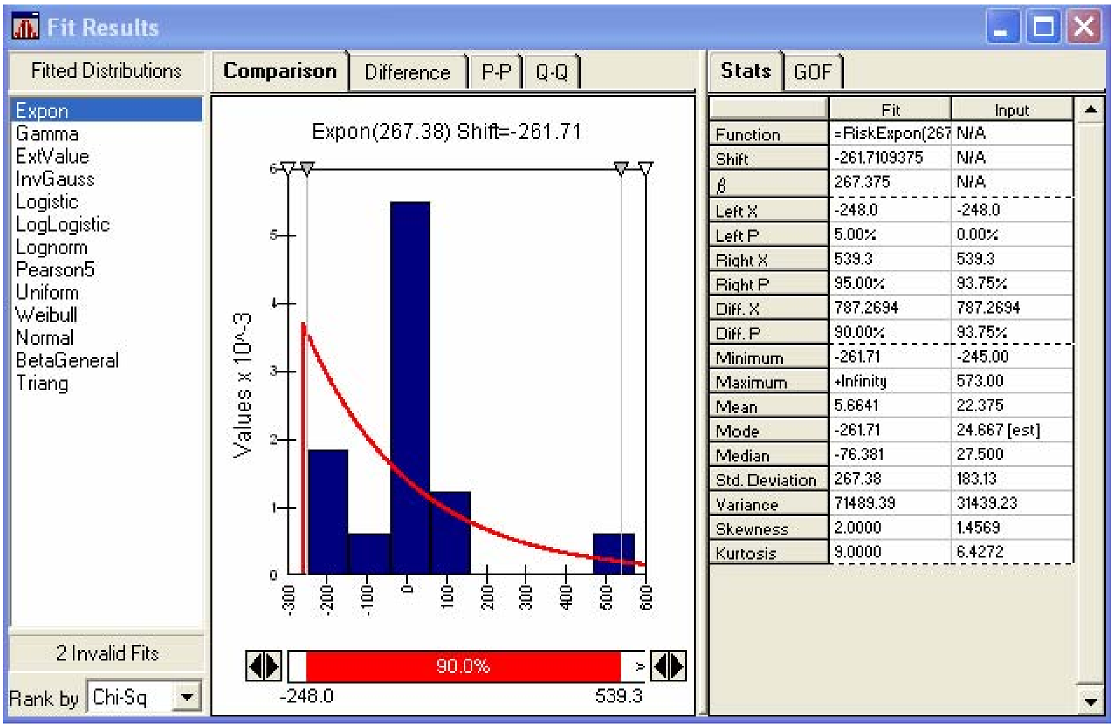

Figure F.7: Difference in activation times between CO and optical detectors

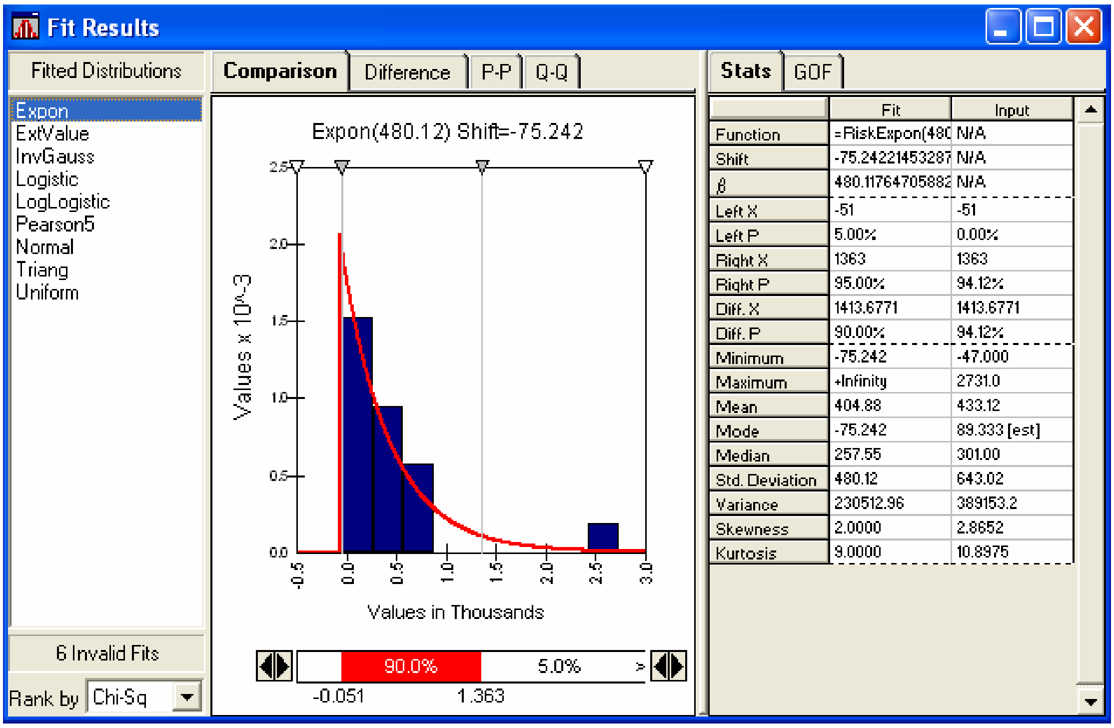

Figure F.8: Difference in activation times between thermal and optical detectors

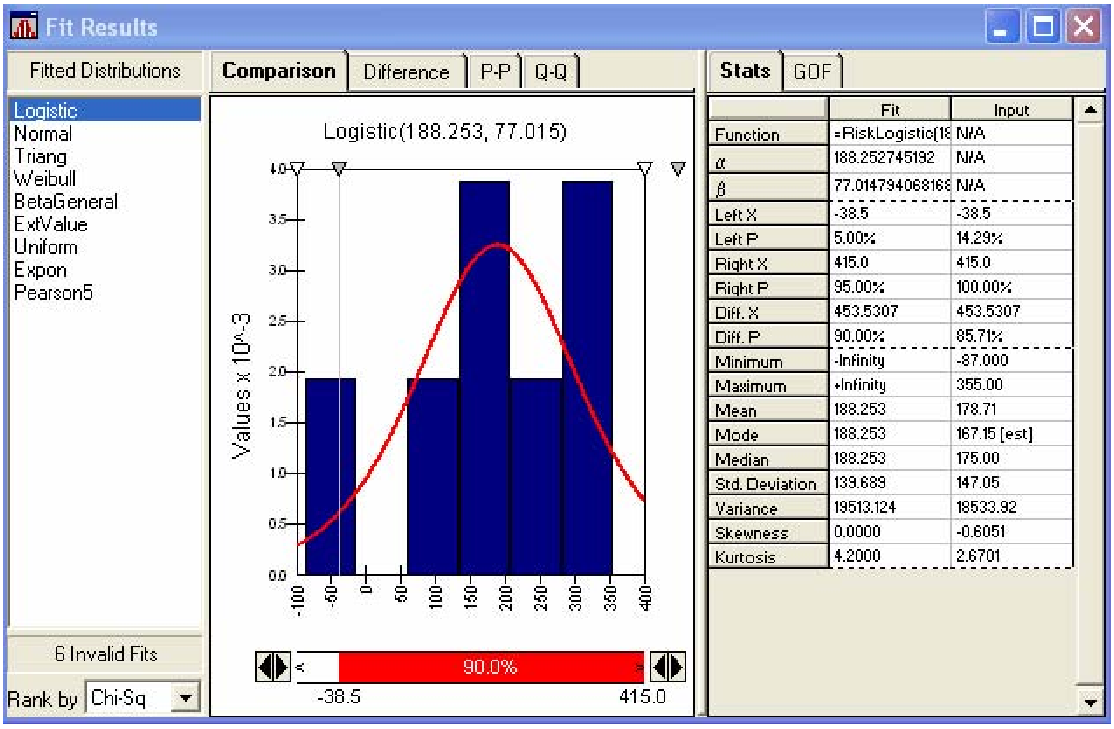

Figure F.9: Difference in activation times between lobby ion and opt detectors

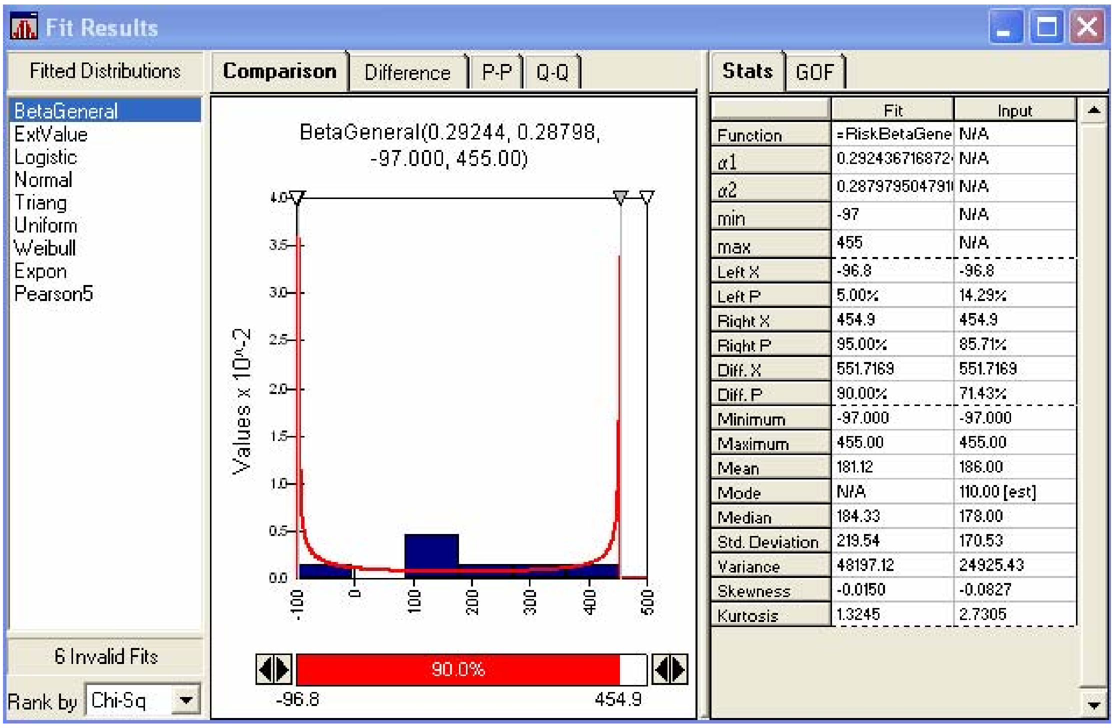

Figure F.10: Difference in activation times between lobby opt and opt detectors

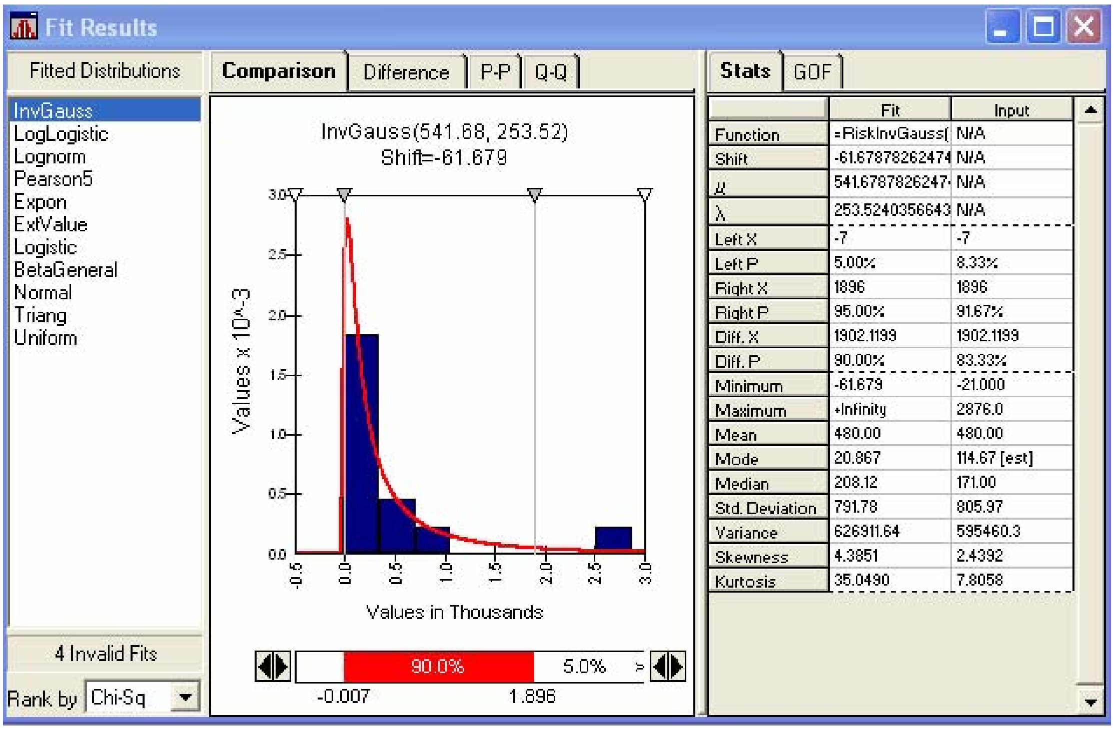

Figure F.11: Difference in activation times between sprinkler and opt detector

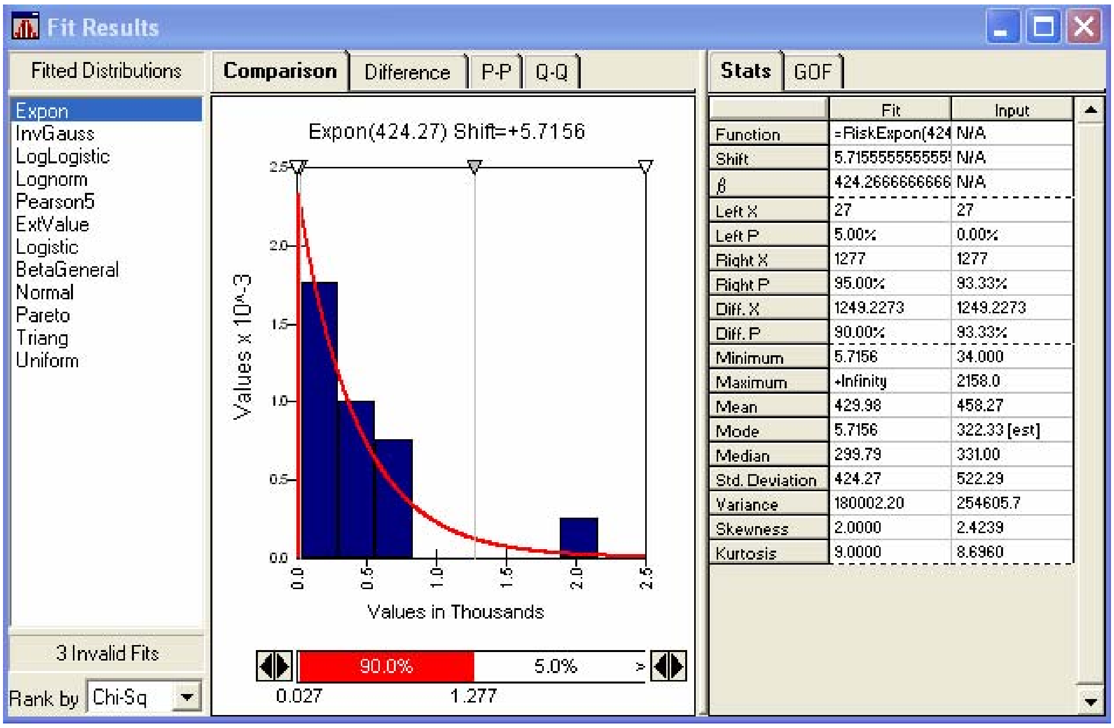

Figure F.12: Difference in activation times between thermal and CO detectors

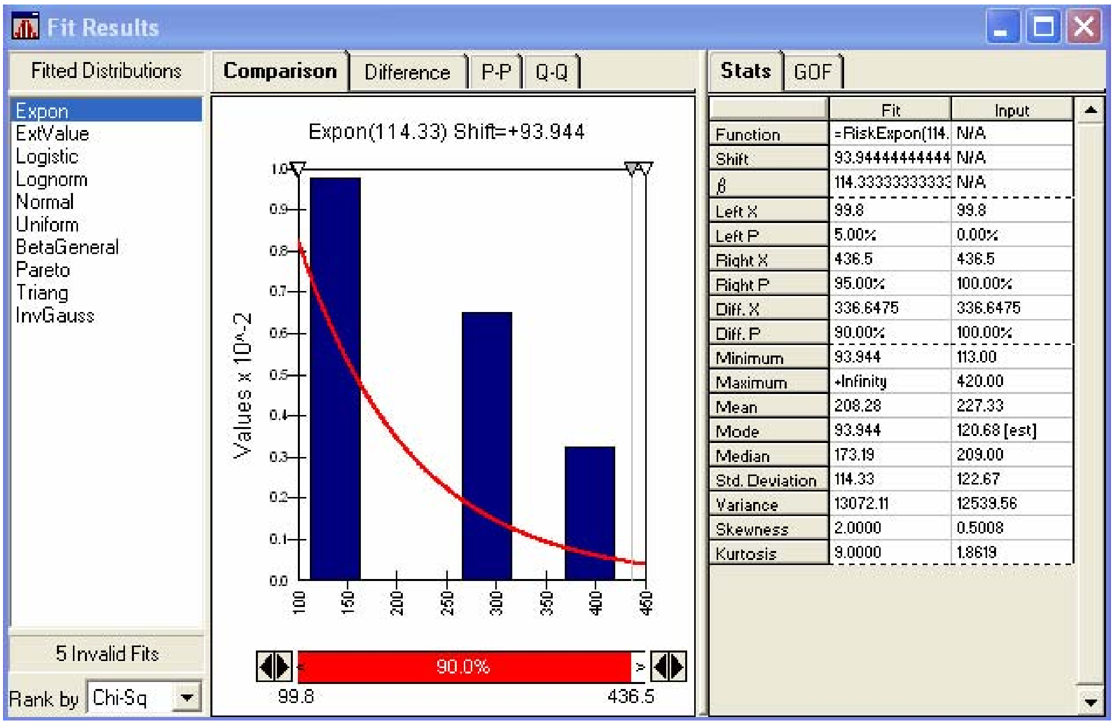

Figure F.13: Difference in activation times between lobby ion and CO detectors

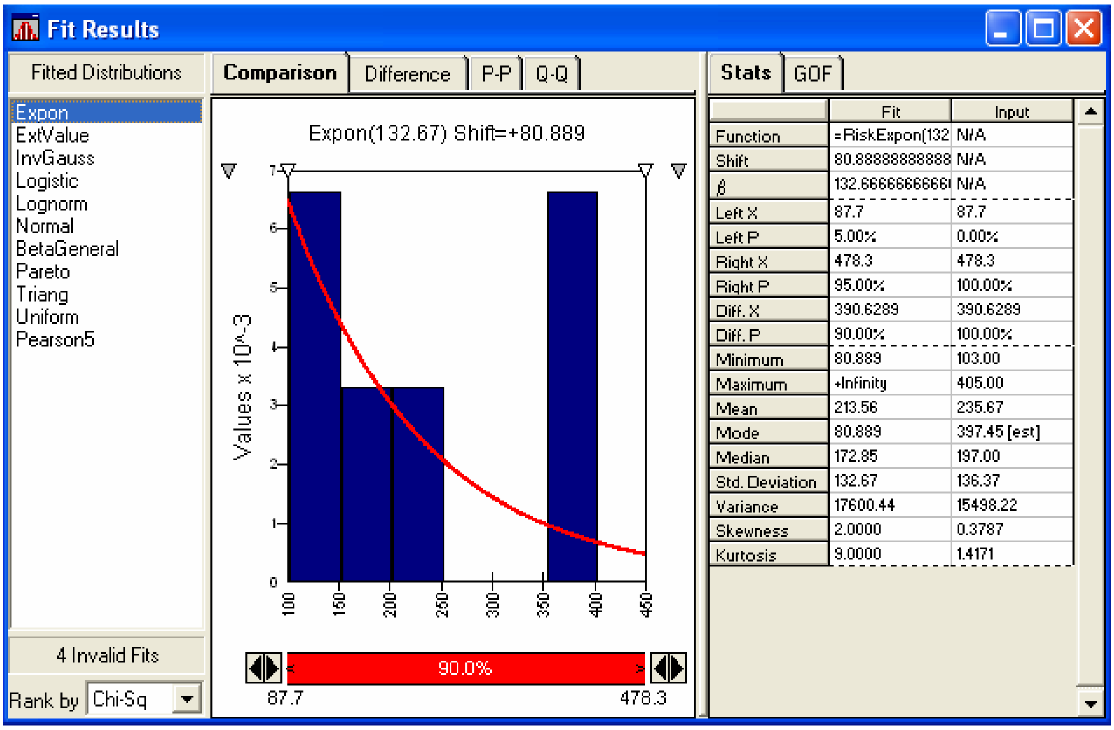

Figure F.14: Difference in activation times between lobby opt and CO detectors

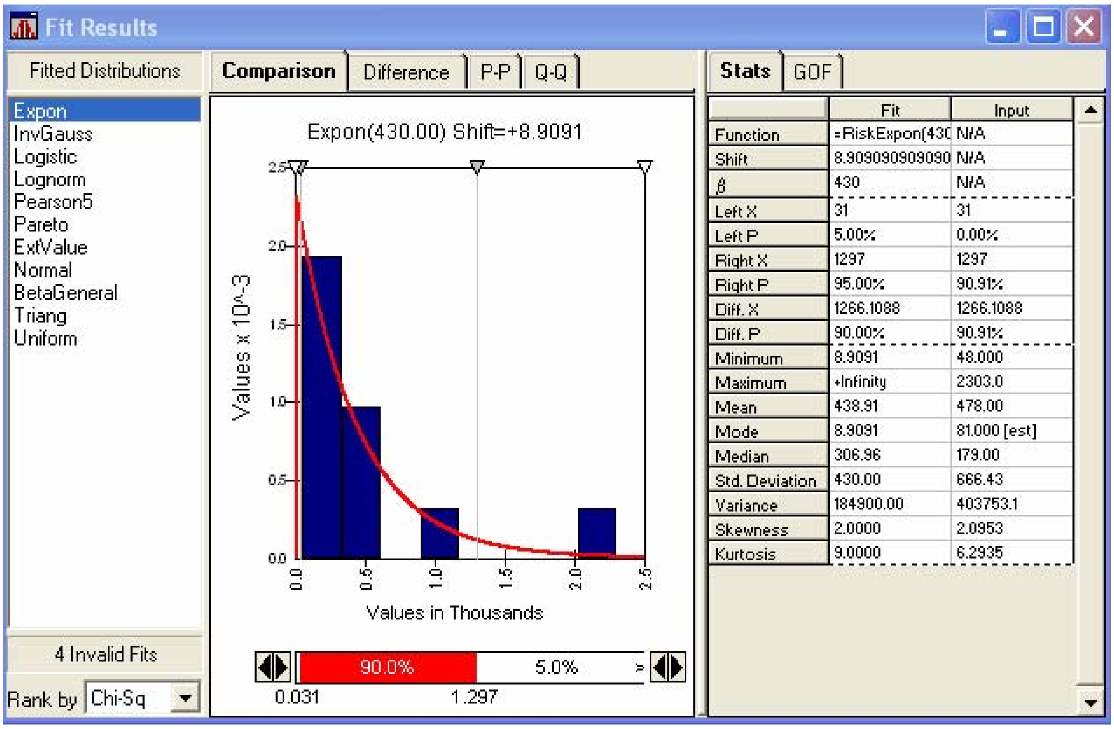

Figure F.15: Difference in activation times between sprinkler and CO detector

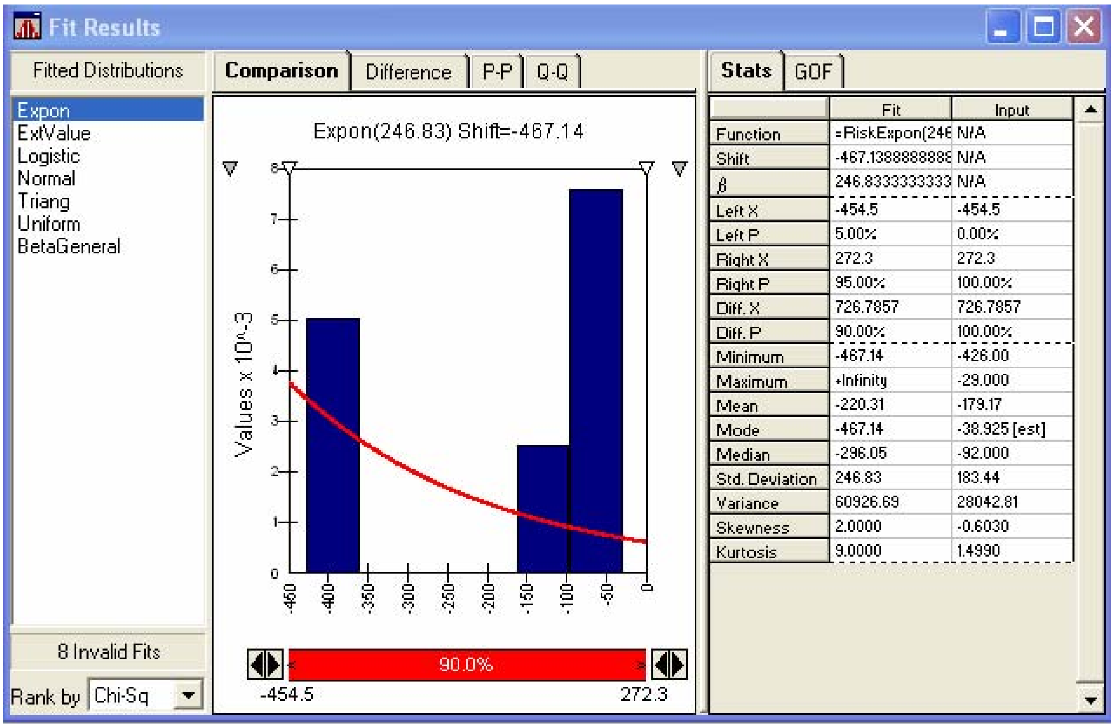

Figure F.16: Difference in activation times lobby ion and thermal detectors

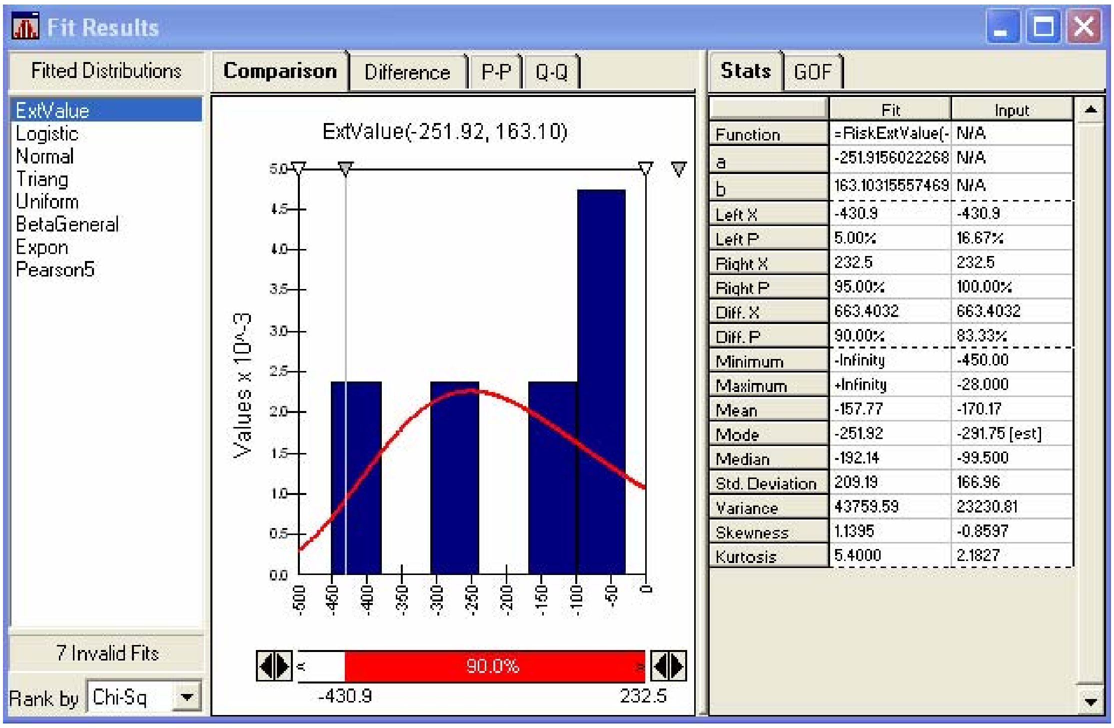

Figure F.17: Difference in activation times lobby optical and thermal detectors

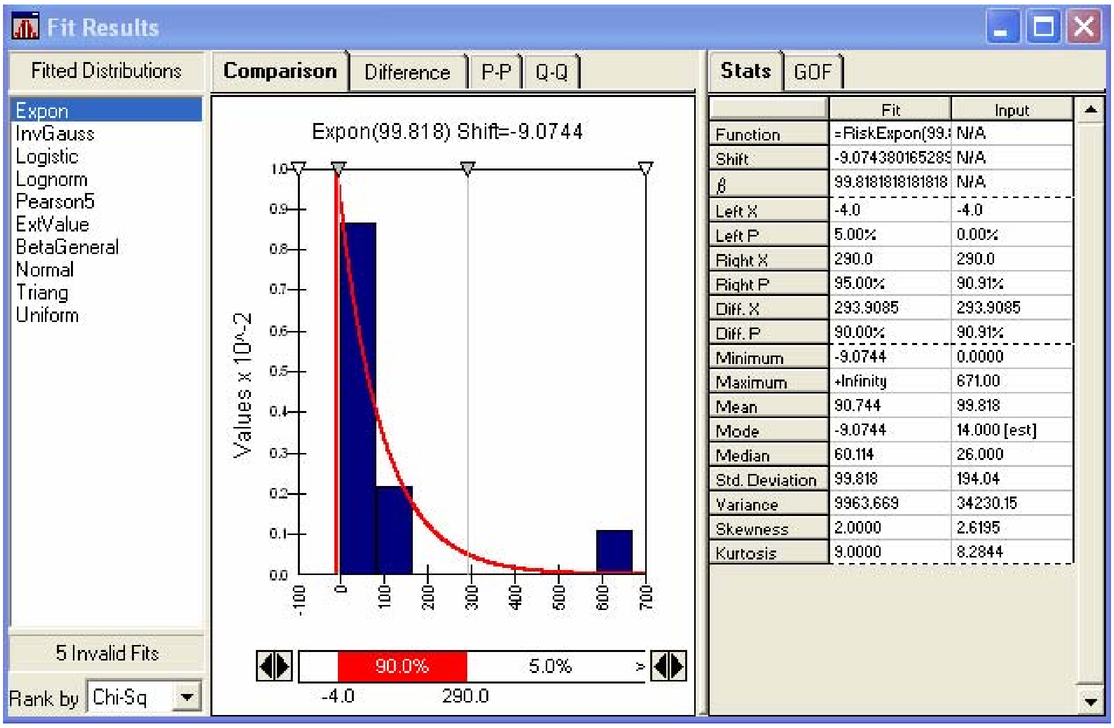

Figure F.18: Difference in activation times sprinkler and thermal detector

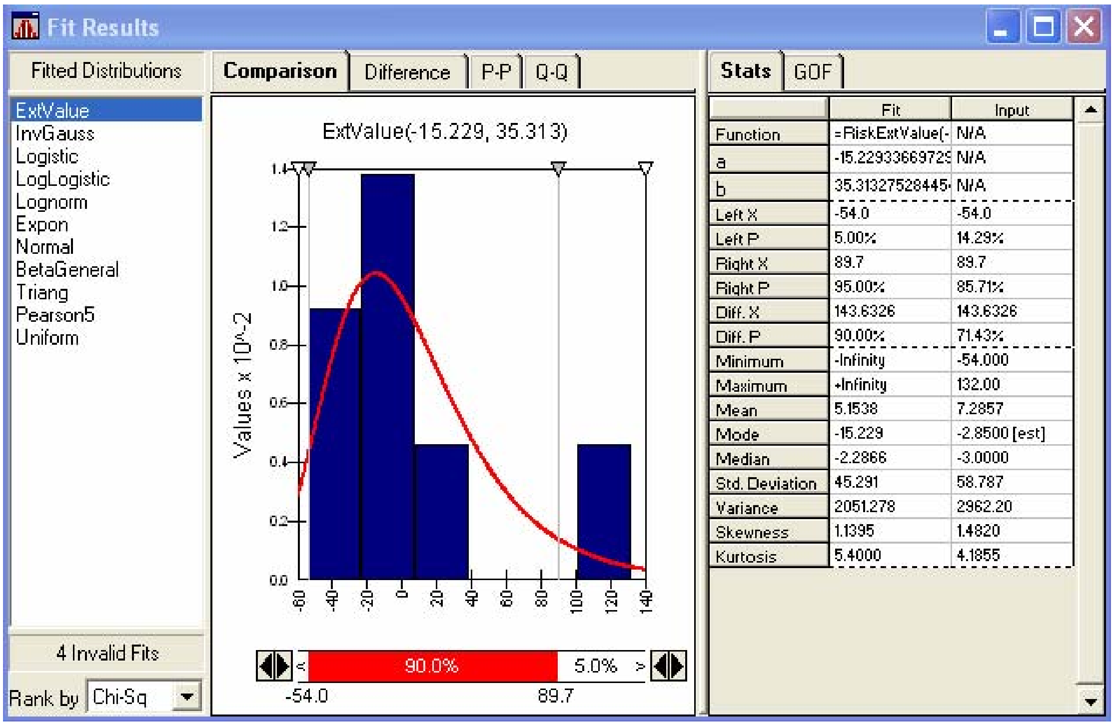

Figure F.19: Difference in activation times lobby opt and lobby ion detectors

Appendix G FEC$_{smoke}$

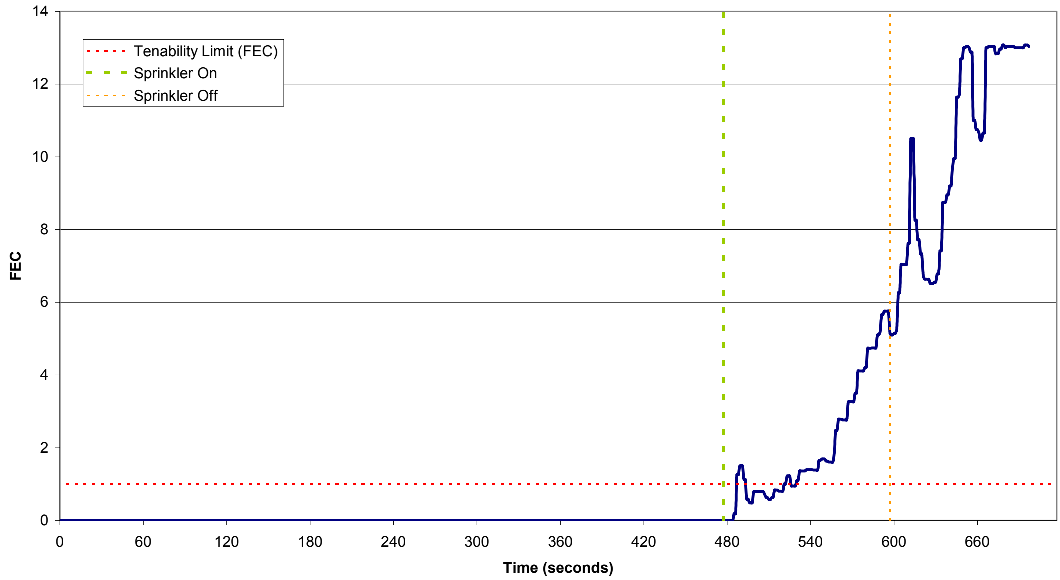

Figure G.1: Test 9 – FEC$_{smoke}$ (800 mm sampling height)

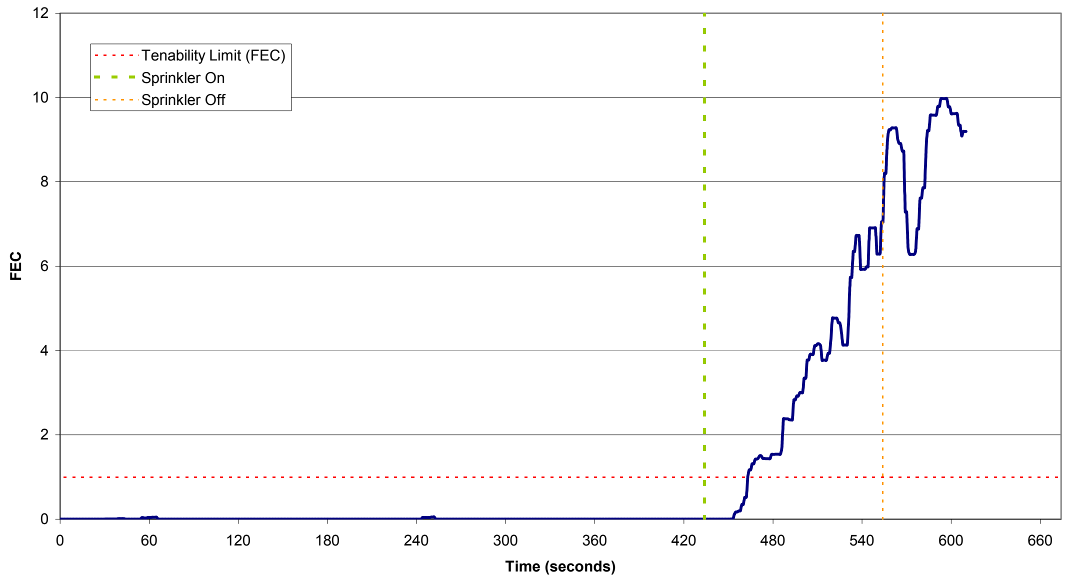

Figure G.2: Test 10 - FEC$_{smoke}$ (800 mm sampling height)

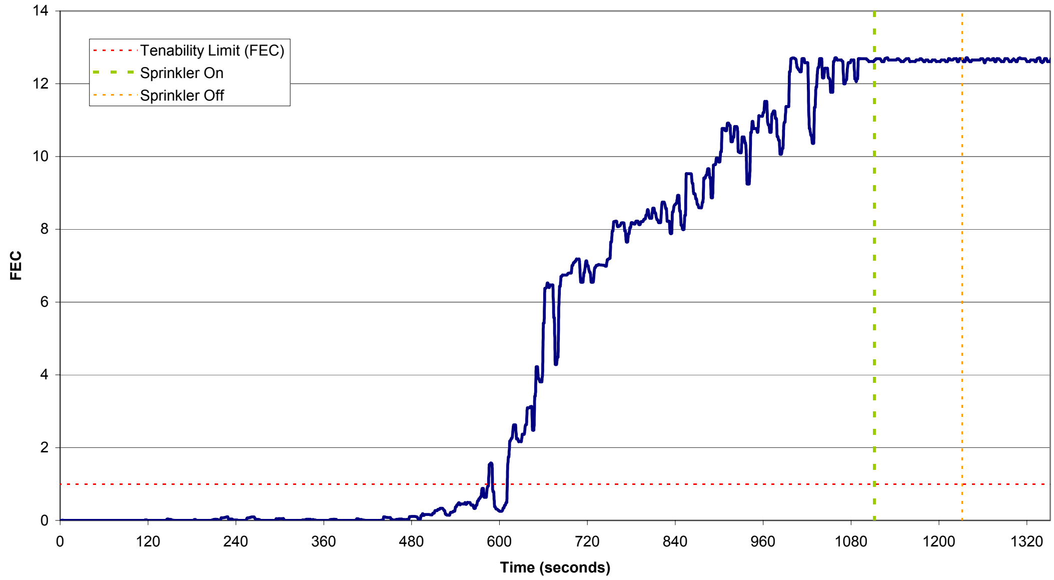

Figure G.3: Test 11 - FEC_{smoke} (800 mm sampling height)

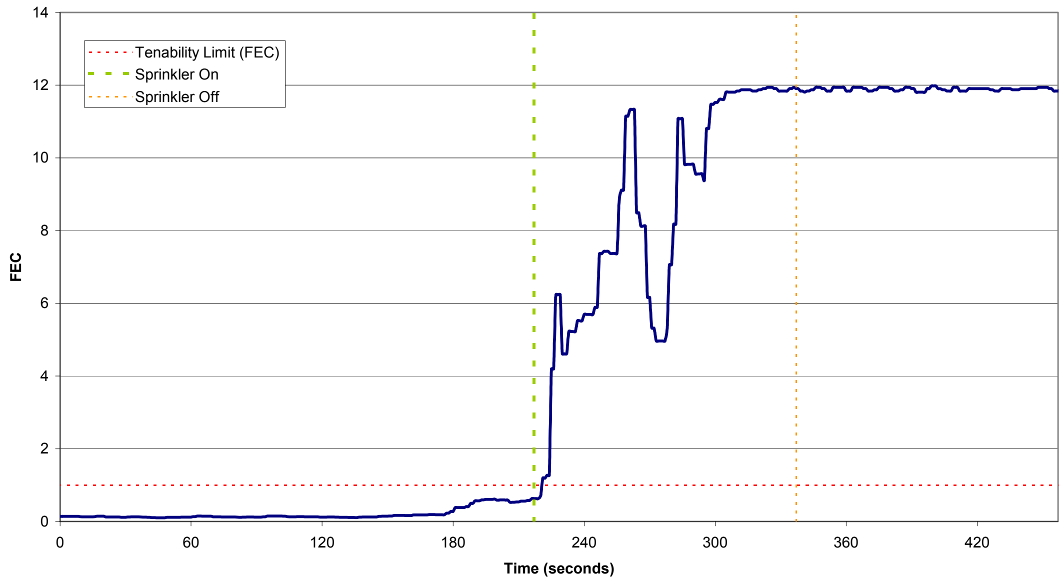

Figure G.4: Test 12 - FEC_{smoke} (800 mm sampling height)

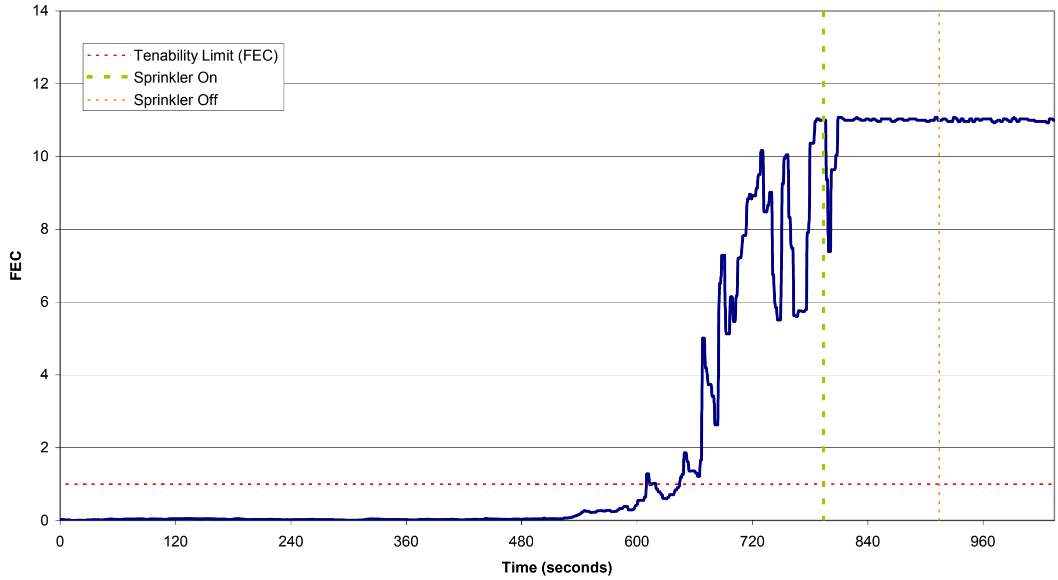

Figure G.5: Test 13 - FEC$_{smoke}$ (800 mm sampling height)

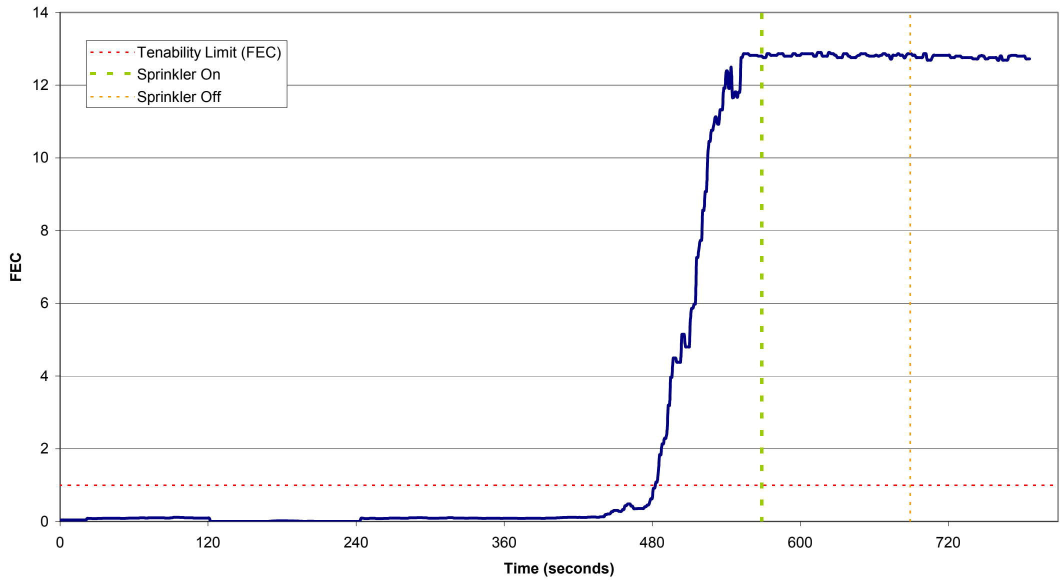

Figure G.6: Test 14 - FEC$_{smoke}$ (1600 mm sampling height)

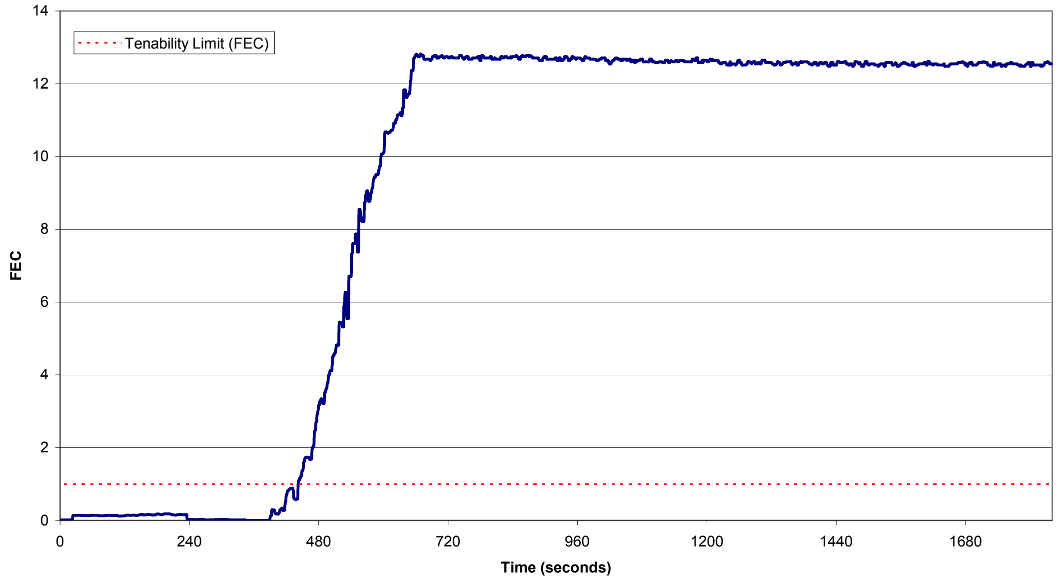

Figure G.7: Test 15 – FEC$_{smoke}$ (1600 mm sampling height)

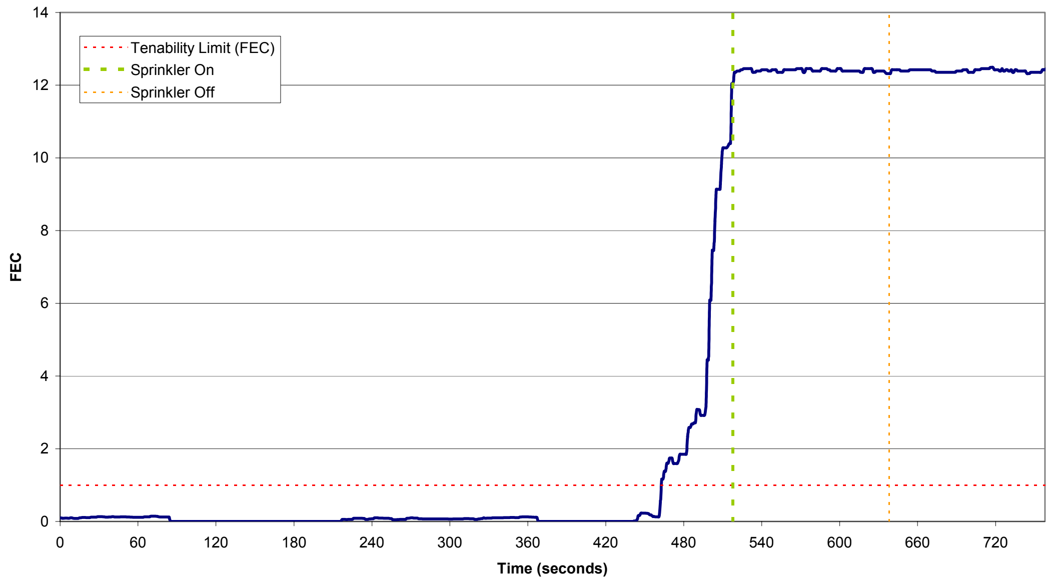

Figure G.8: Test 16 – FEC$_{smoke}$ (1600 mm sampling height)

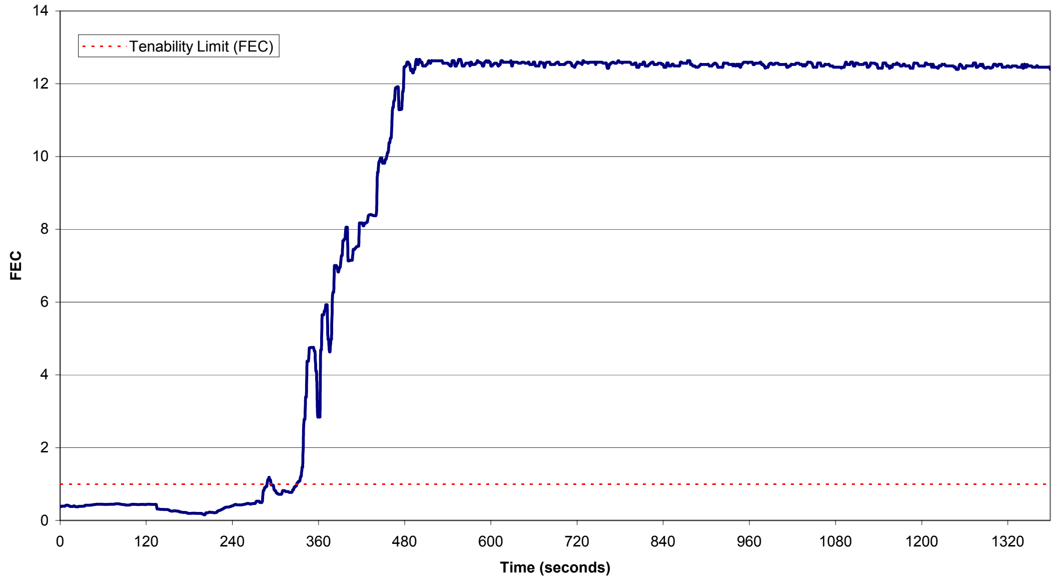

Figure G.9: Test 17 – FEC$_{smoke}$ (800 mm sampling height)

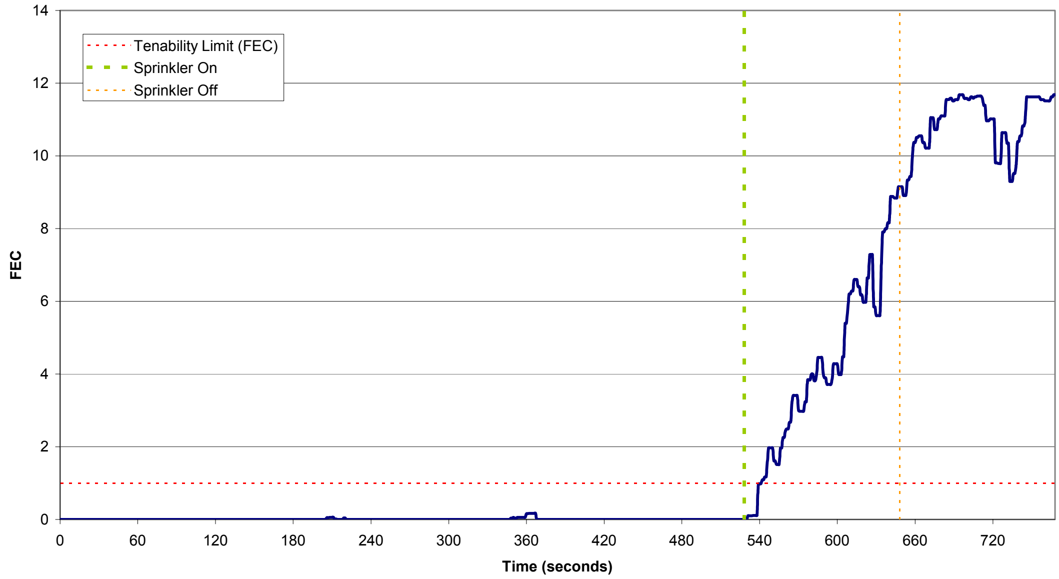

Figure G.10: Test 18 – FEC$_{smoke}$ (800 mm sampling height)

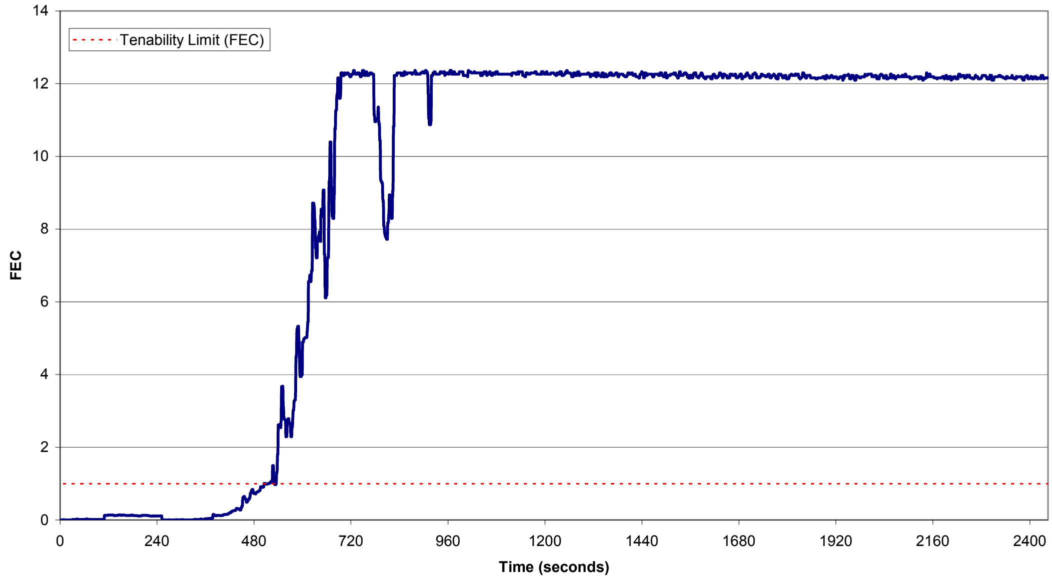

Figure G.11: Test 20 – FEC_{smoke} (800 mm sampling height)

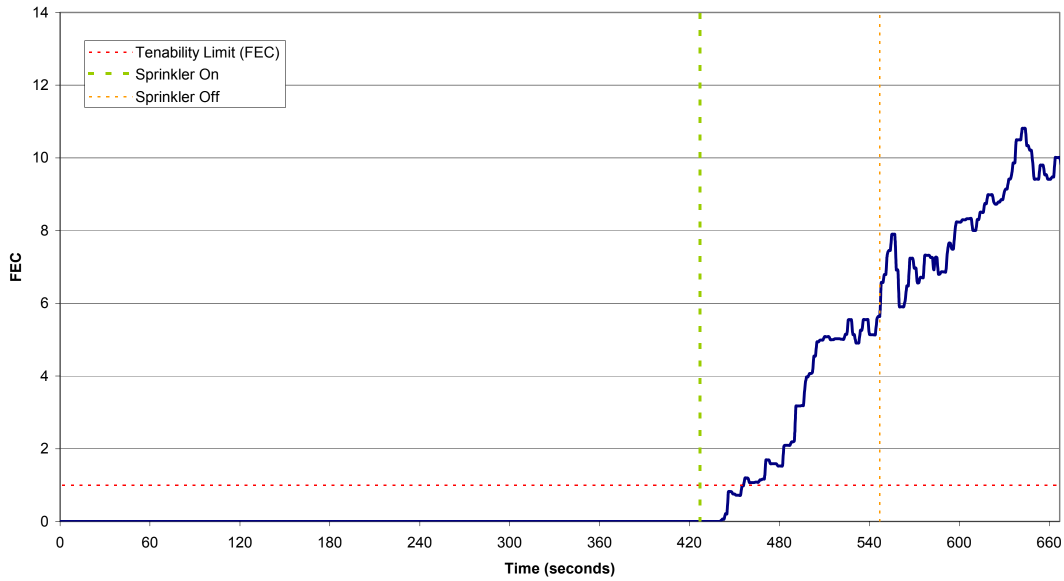

Figure G.12: Test 21 – FEC_{smoke} (800 mm sampling height)

Appendix H Temperature

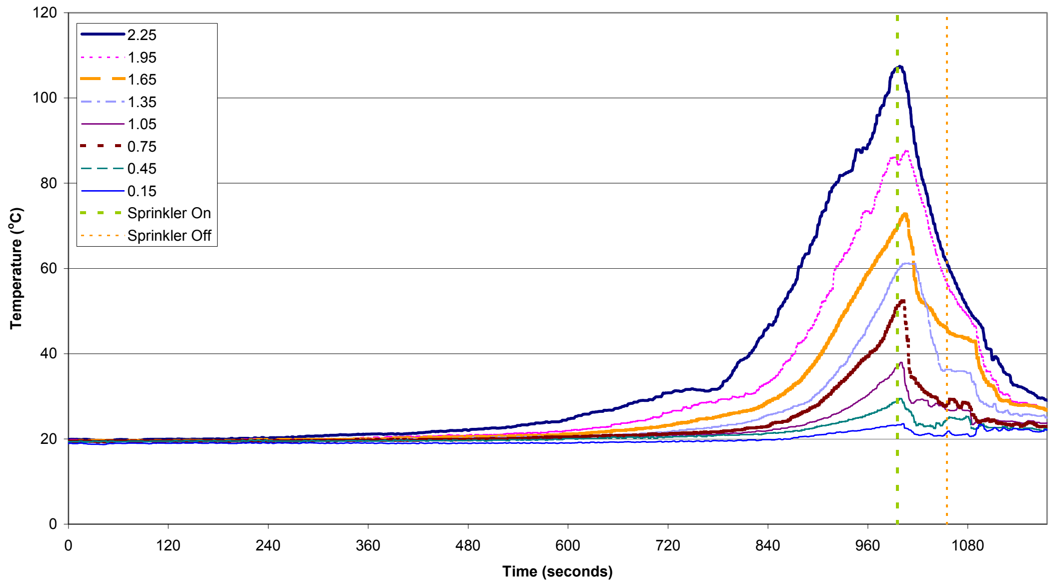

Figure H.1: Test 1 - Centre room temperature profile

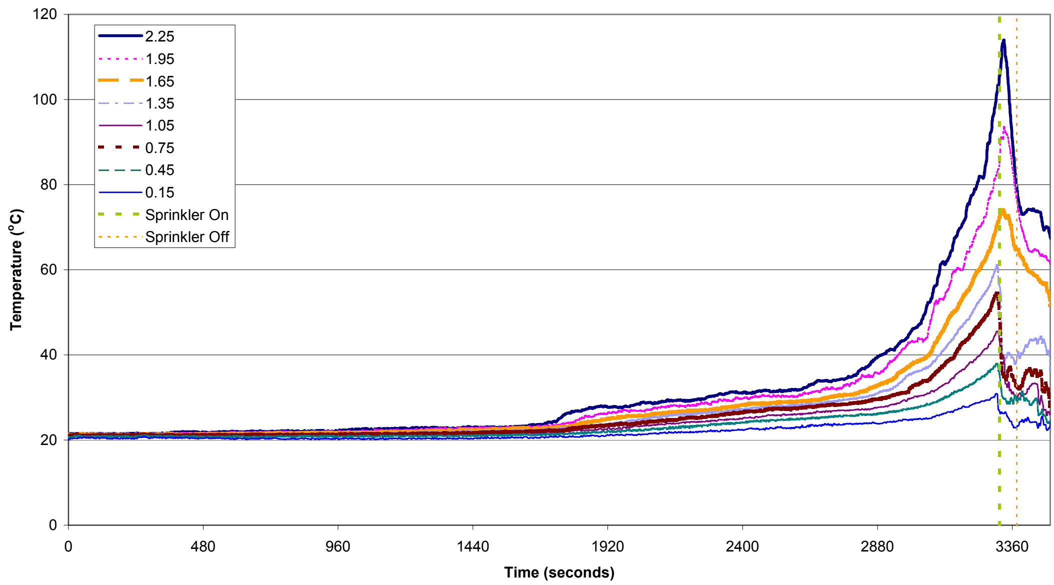

Figure H.2: Test 2 - Centre room temperature profile

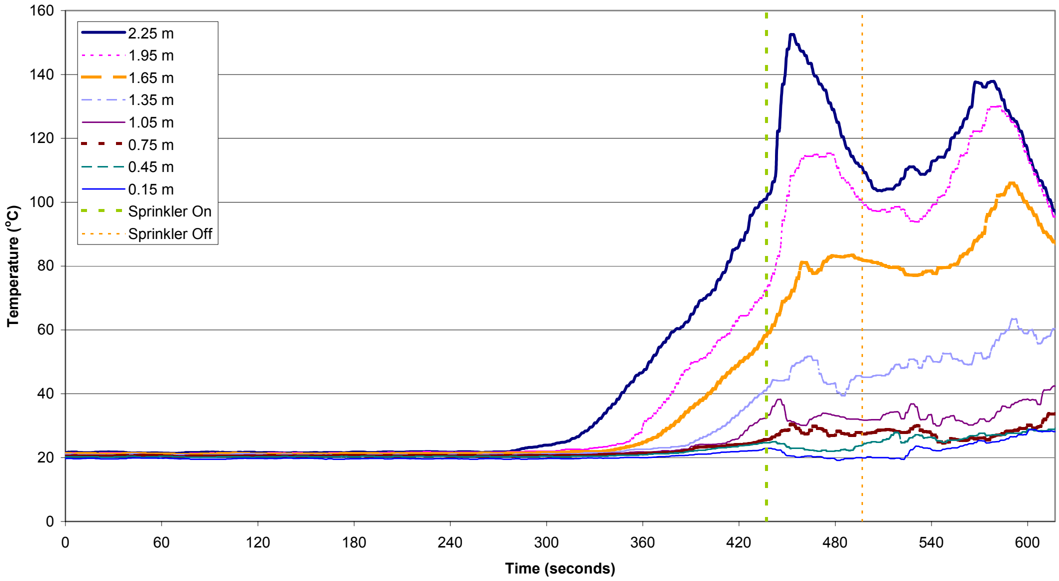

Figure H.3: Test 3 - Centre room temperature profile

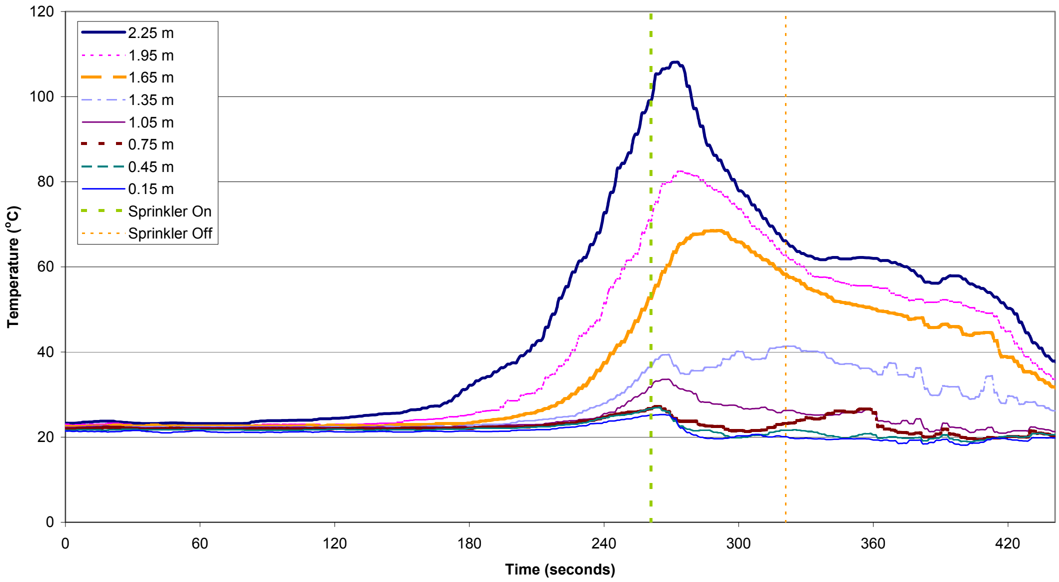

Figure H.4: Test 4 - Centre room temperature profile

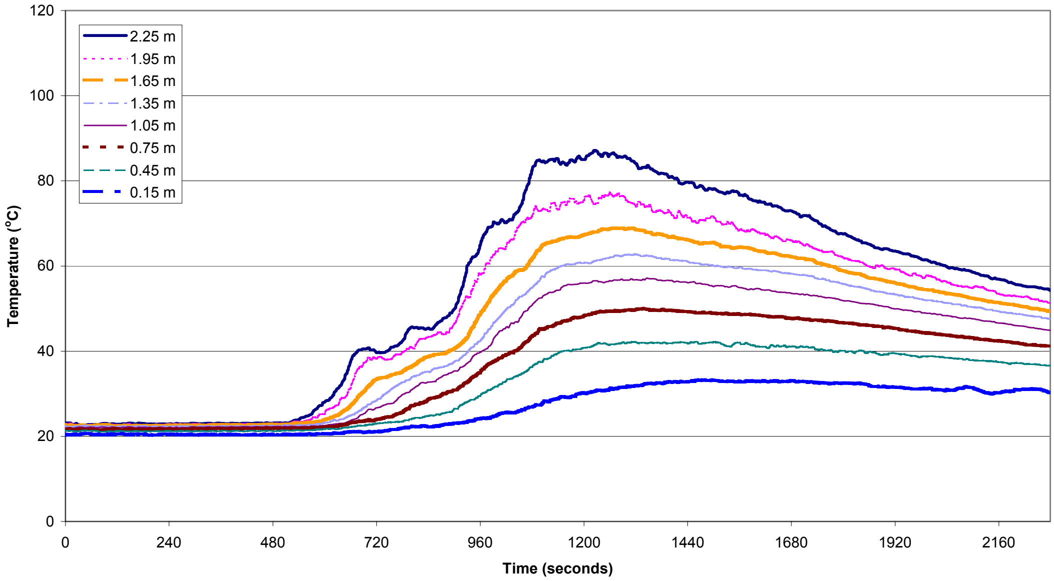

Figure H.5: Test 5 - Centre room temperature profile

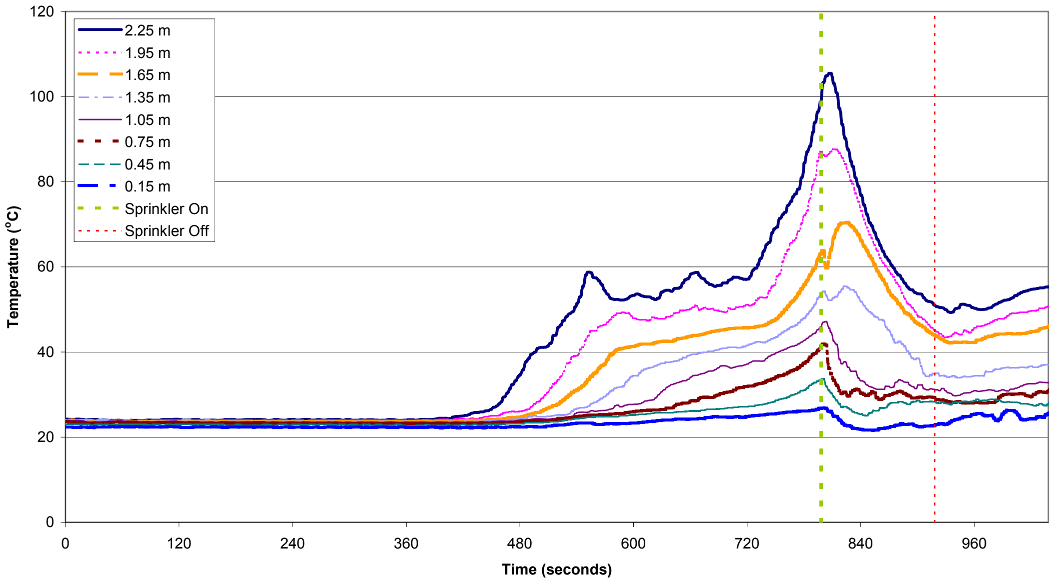

Figure H.6: Test 6 - Centre room temperature profile

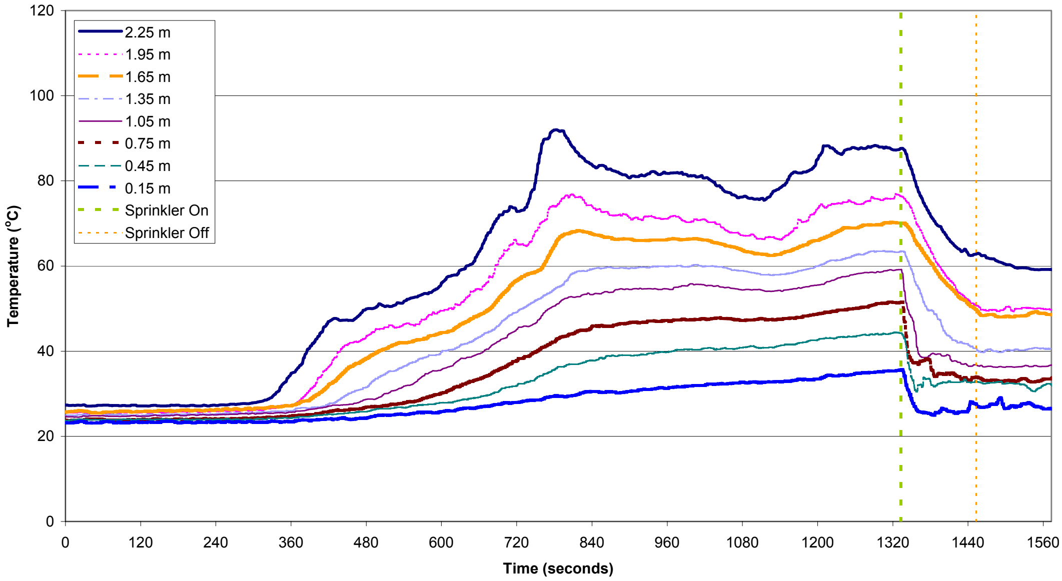

Figure H.7: Test 7 - Centre room temperature profile

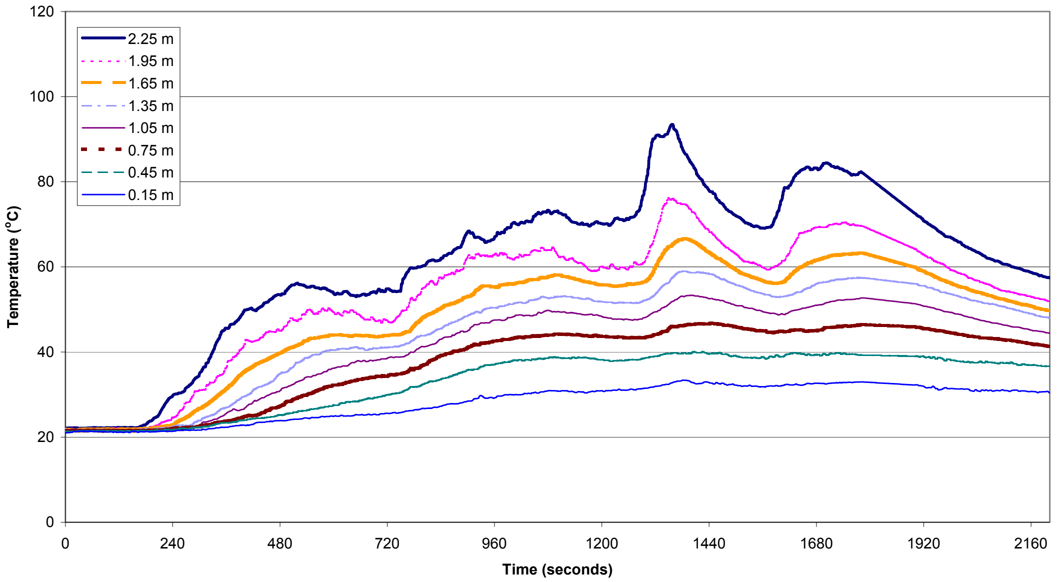

Figure H.8: Test 8 - Centre room temperature profile

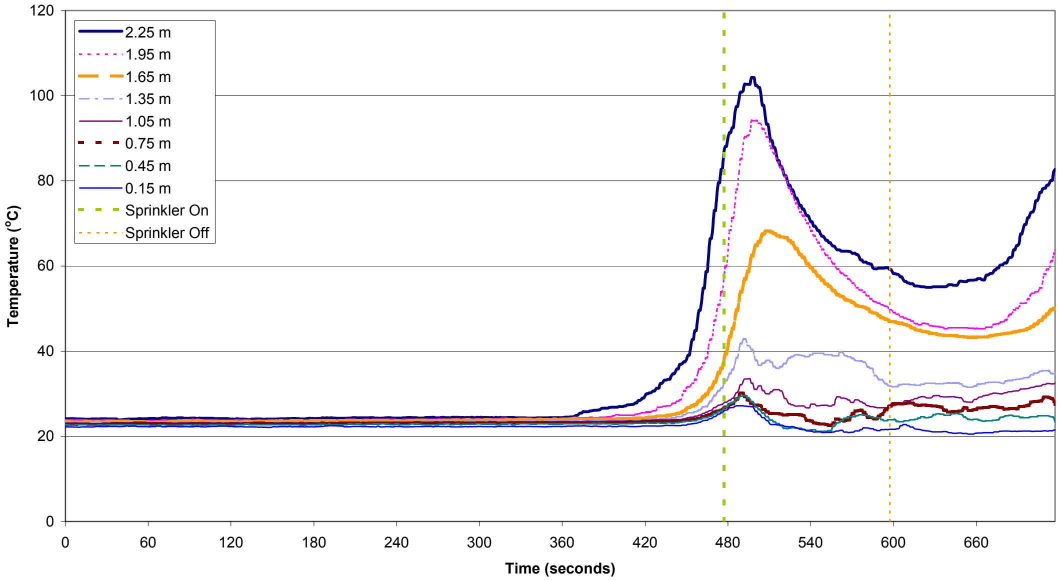

Figure H.9: Test 9 - Centre room temperature profile

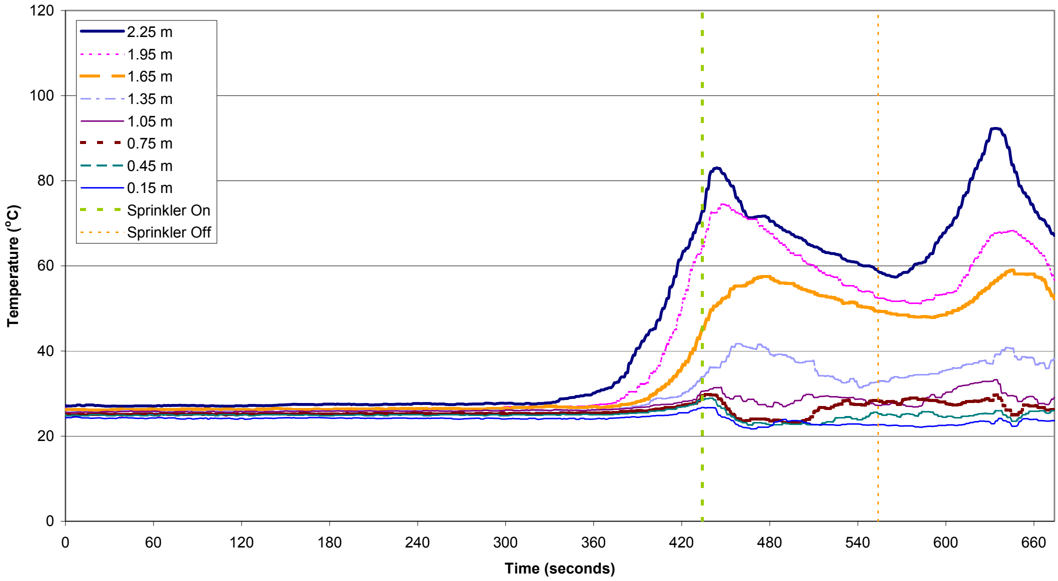

Figure H.10: Test 10 - Centre room temperature profile

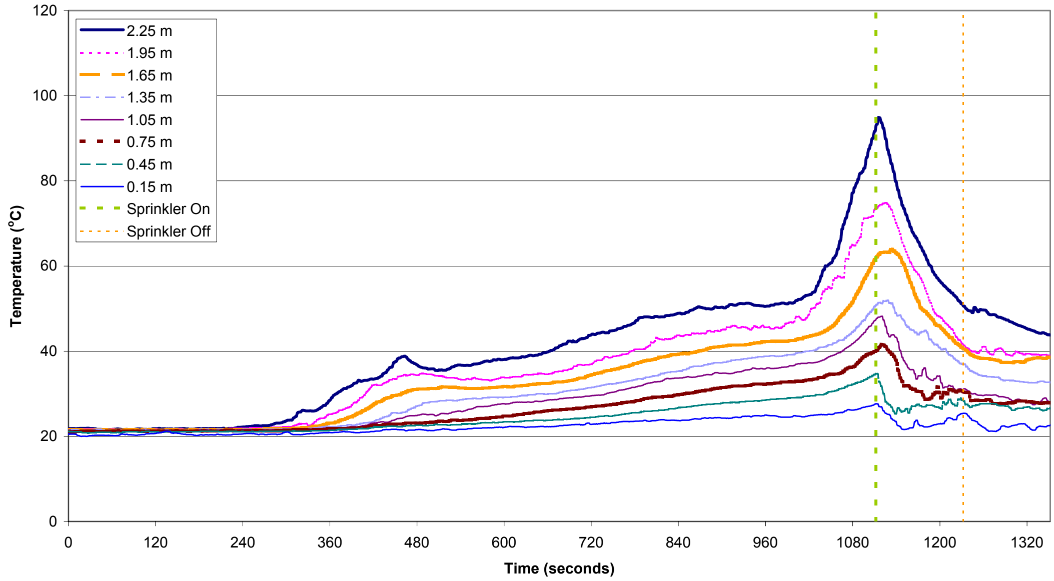

Figure H.11: Test 11 - Centre room temperature profile

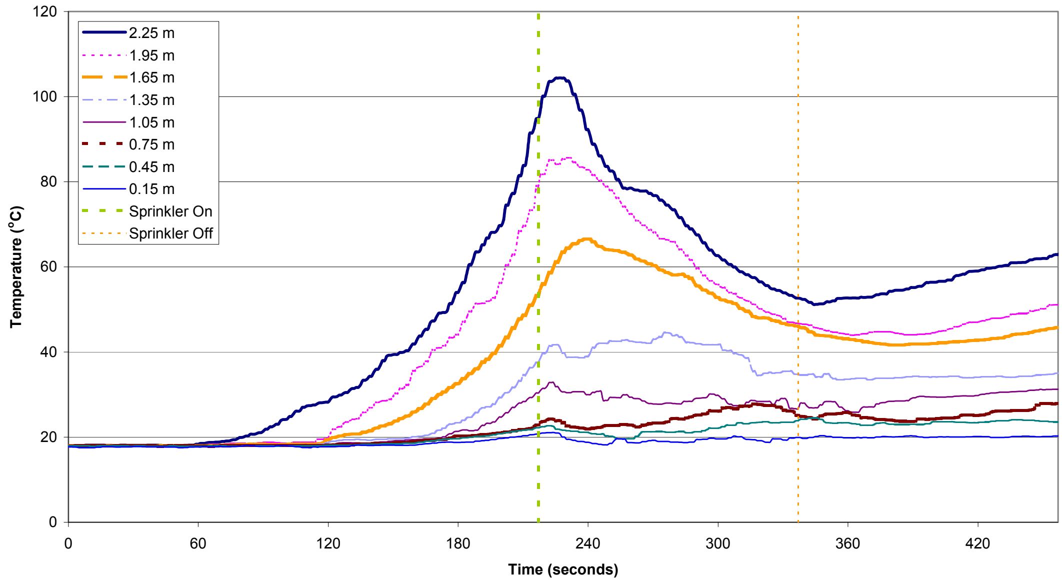

Figure H.12: Test 12 - Centre room temperature profile

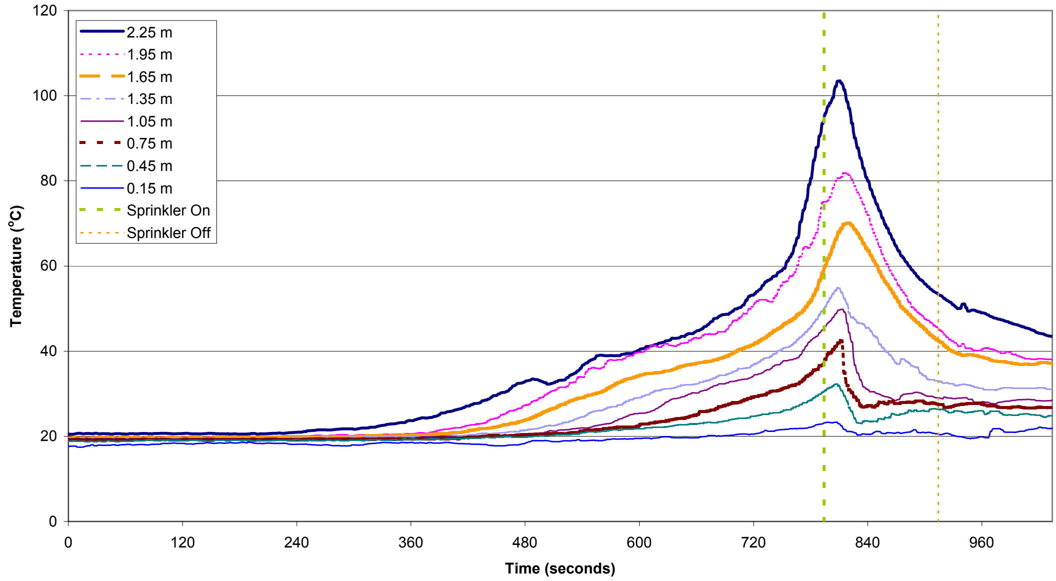

Figure H.13: Test 13 - Centre room temperature profile

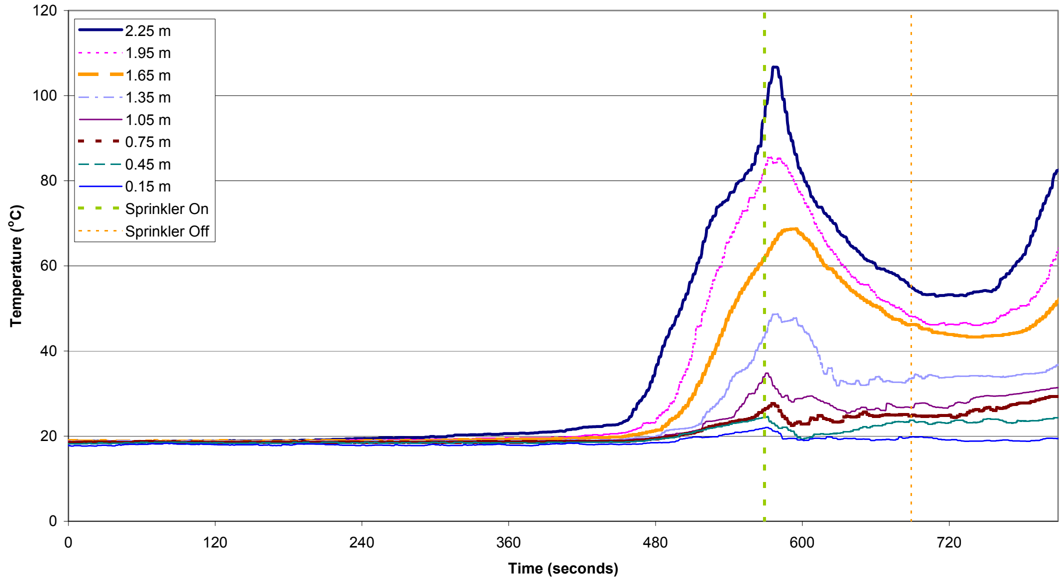

Figure H.14: Test 14 - Centre room temperature profile

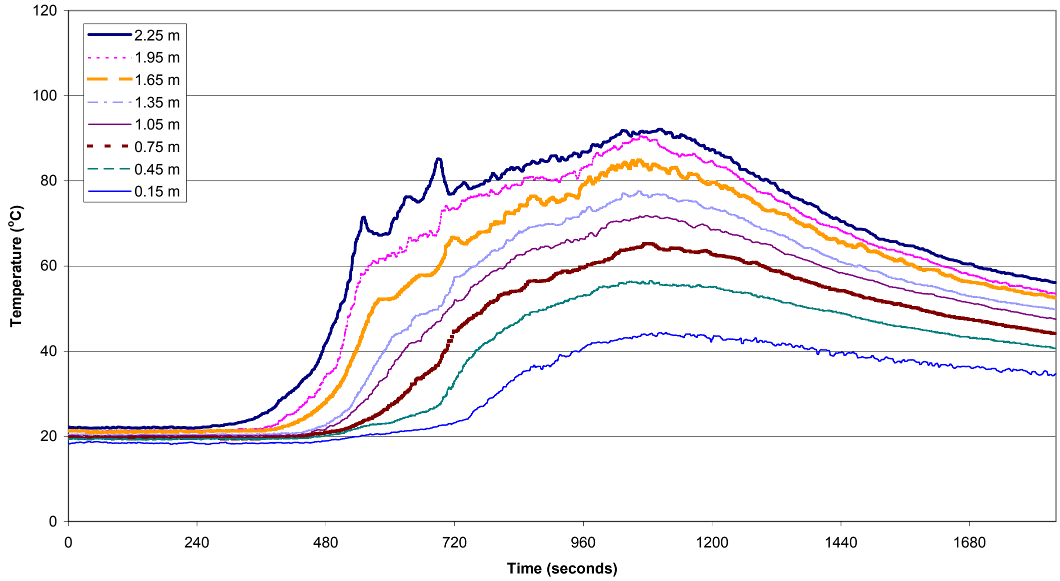

Figure H.15: Test 15 - Centre room temperature profile

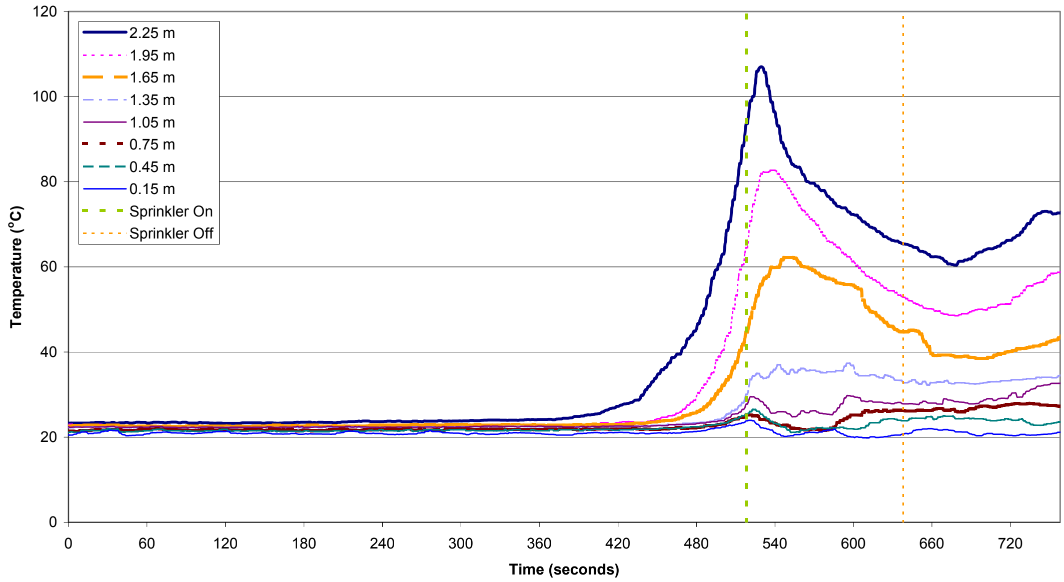

Figure H.16: Test 16 - Centre room temperature profile

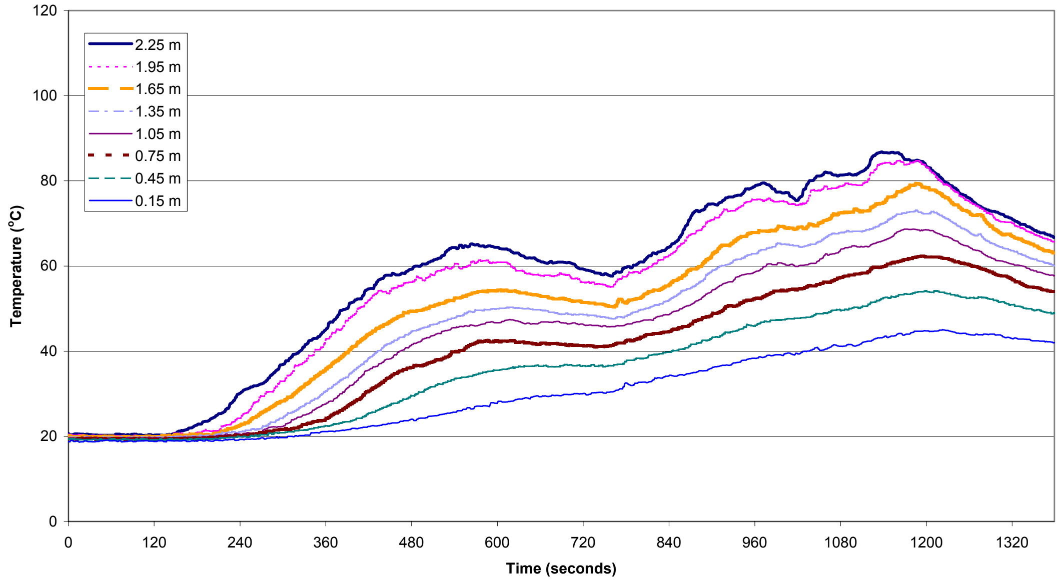

Figure H.17: Test 17 - Centre room temperature profile

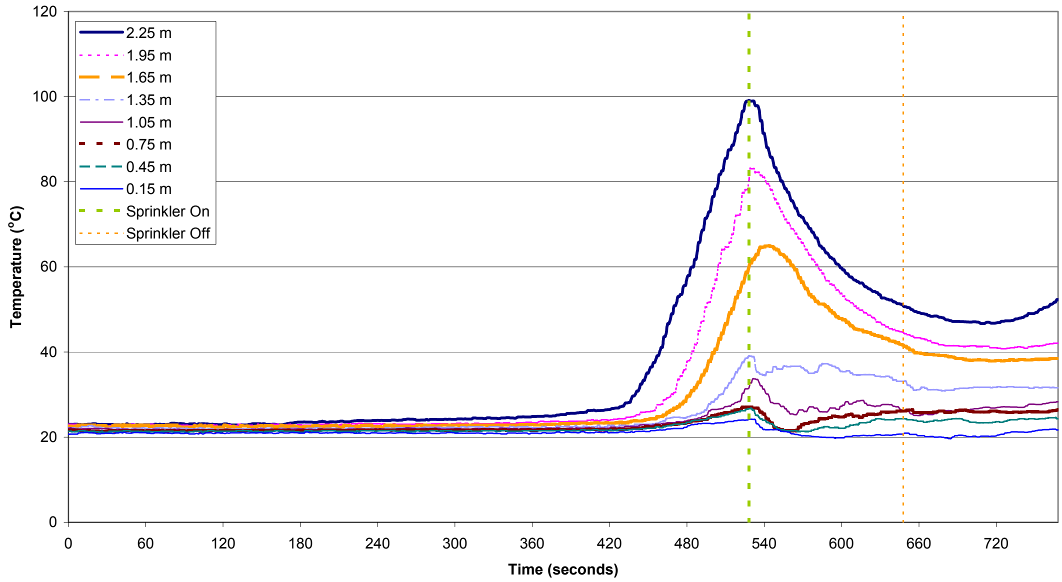

Figure H.18: Test 18 - Centre room temperature profile

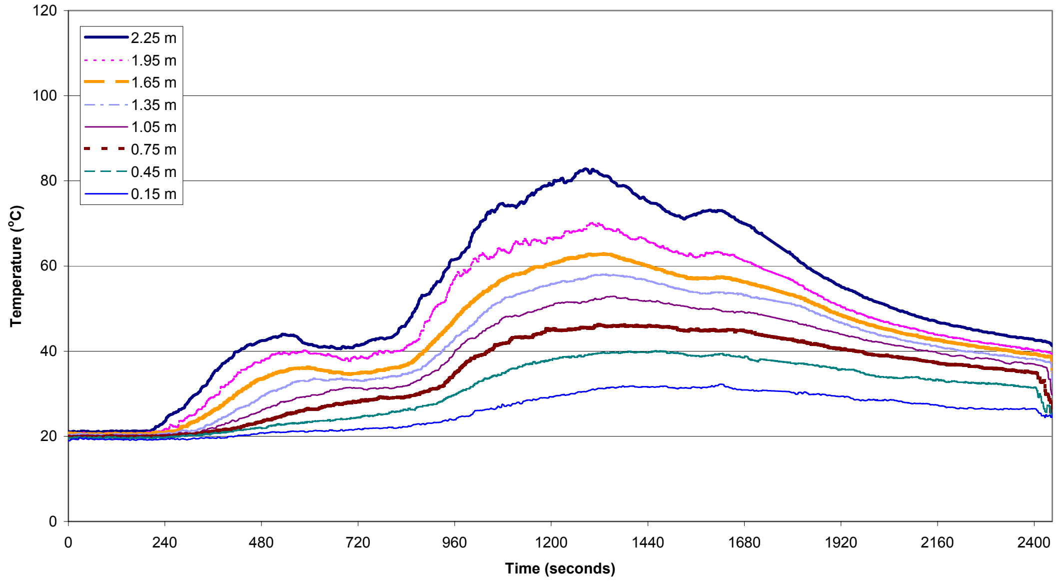

Figure H.20: Test 20 - Centre room temperature profile

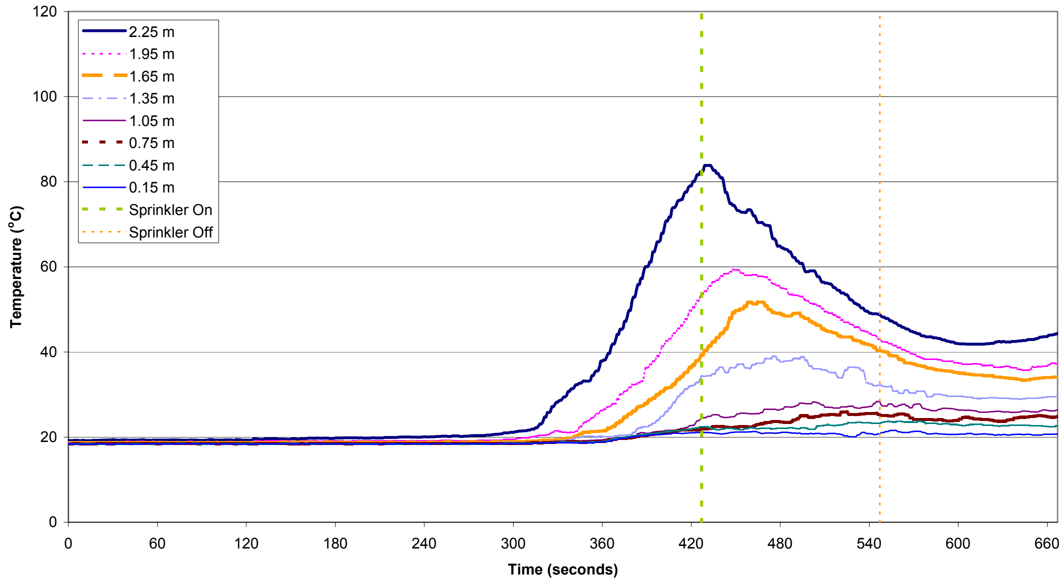

Figure H.21: Test 21 - Centre room temperature profile

Appendix I Heat Release Rate

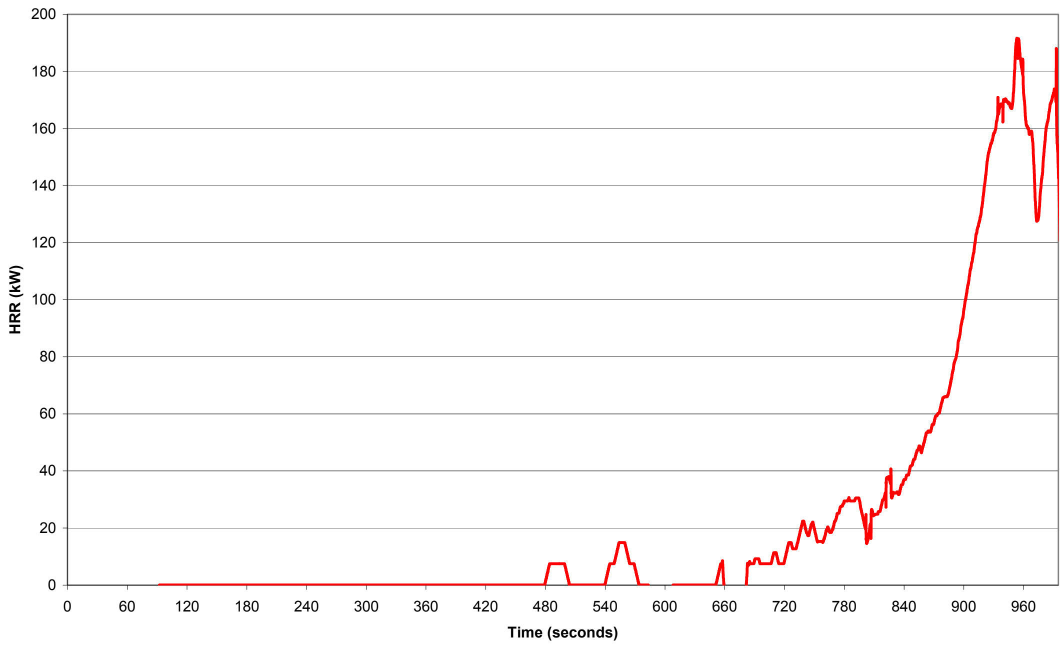

Figure I.1: Test 1 – Heat release rate

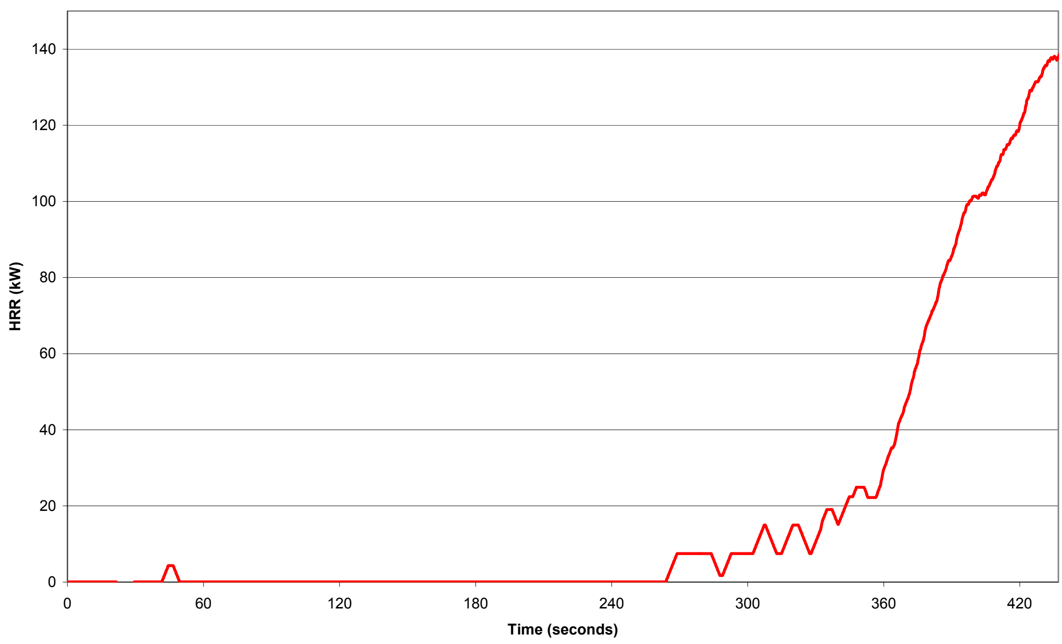

Figure I.2: Test 3 – Heat release rate

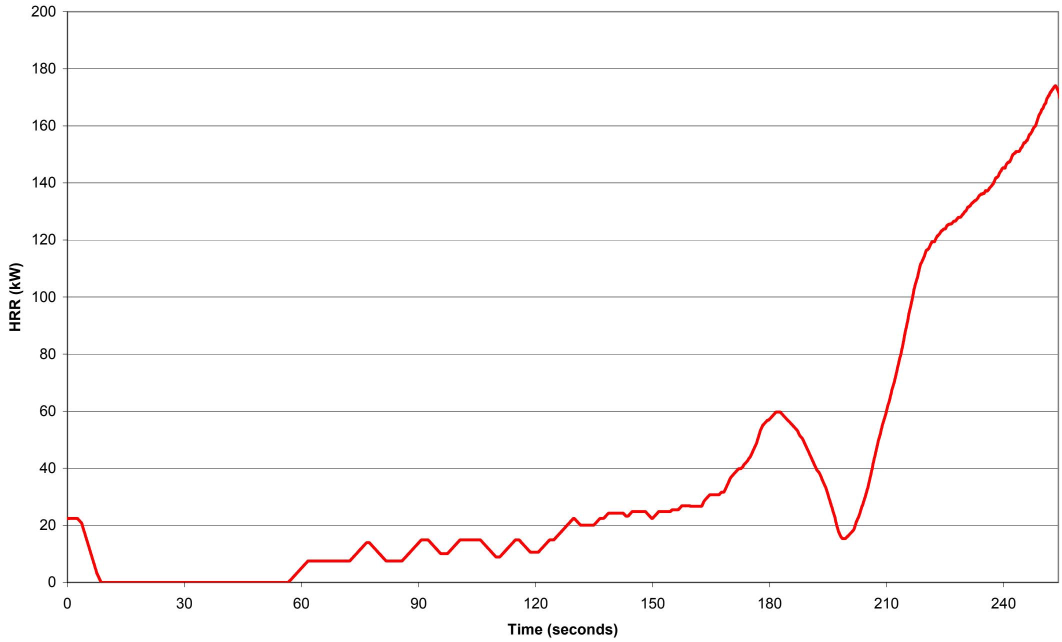

Figure I.3: Test 4 – Heat release rate

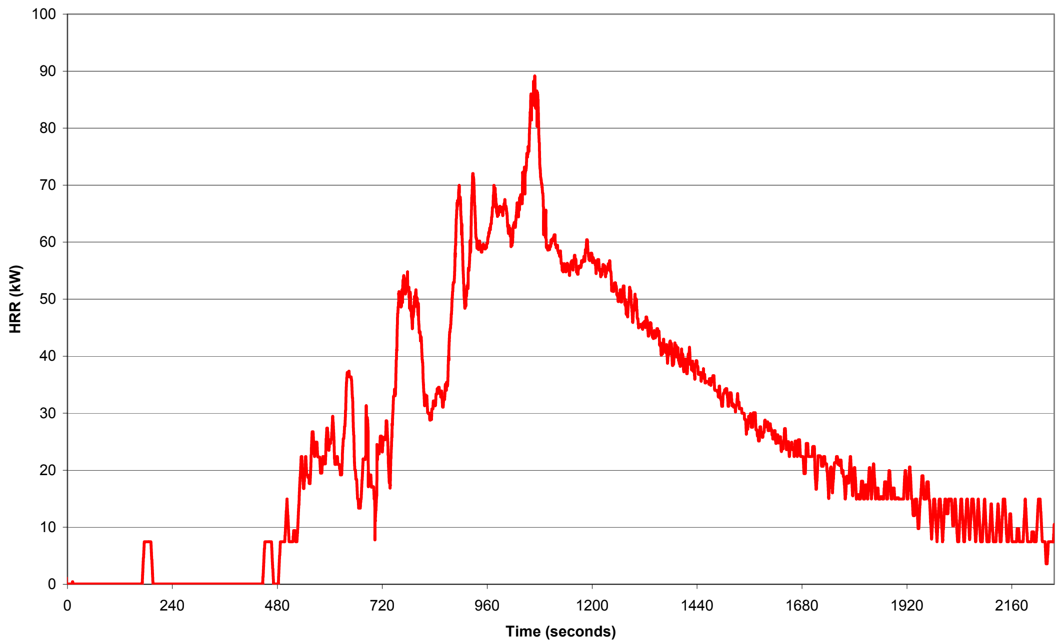

Figure I.4: Test 5 – Heat release rate

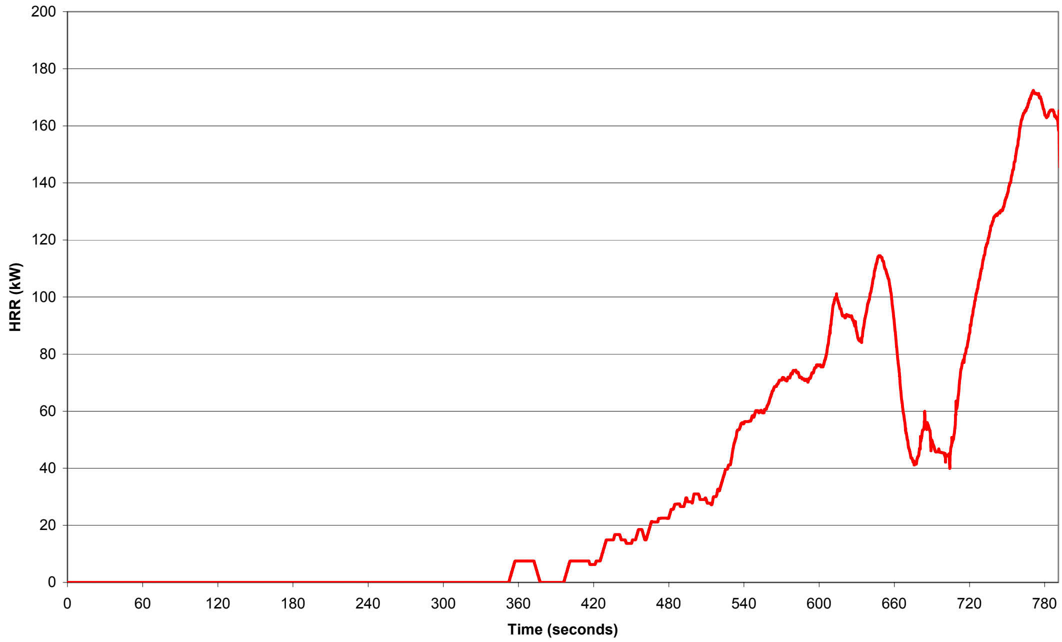

Figure I.5: Test 6 – Heat release rate

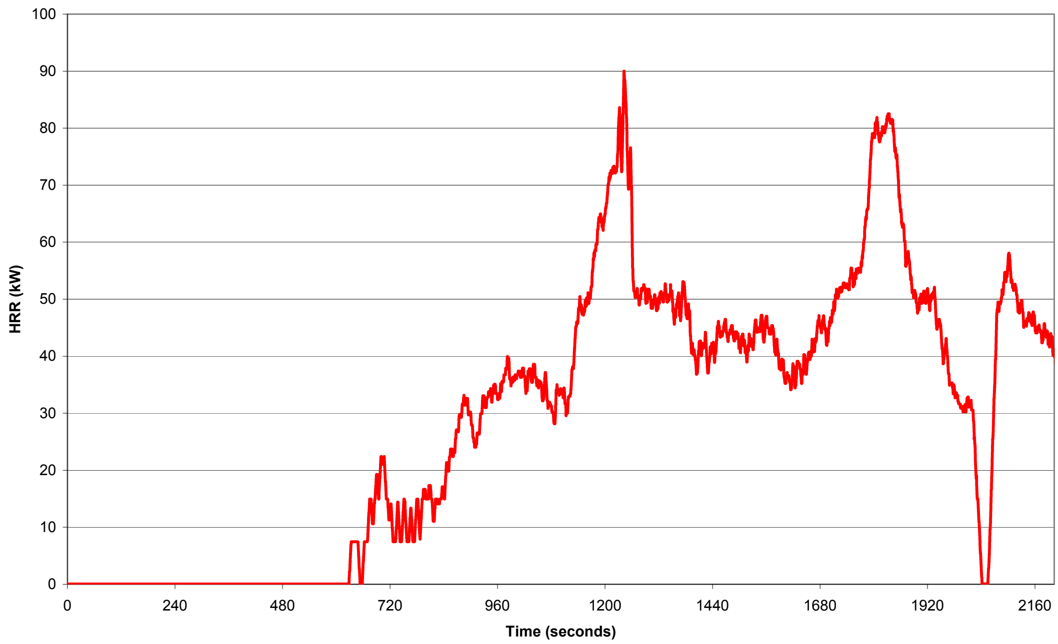

Figure I.6: Test 8 – Heat release rate

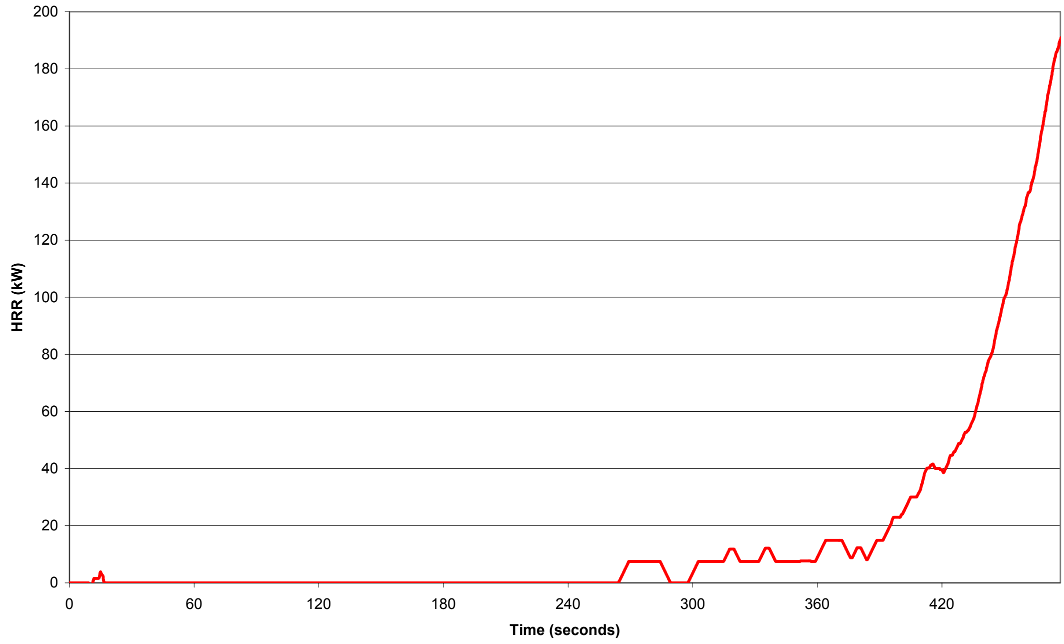

Figure I.7: Test 9 – Heat release rate

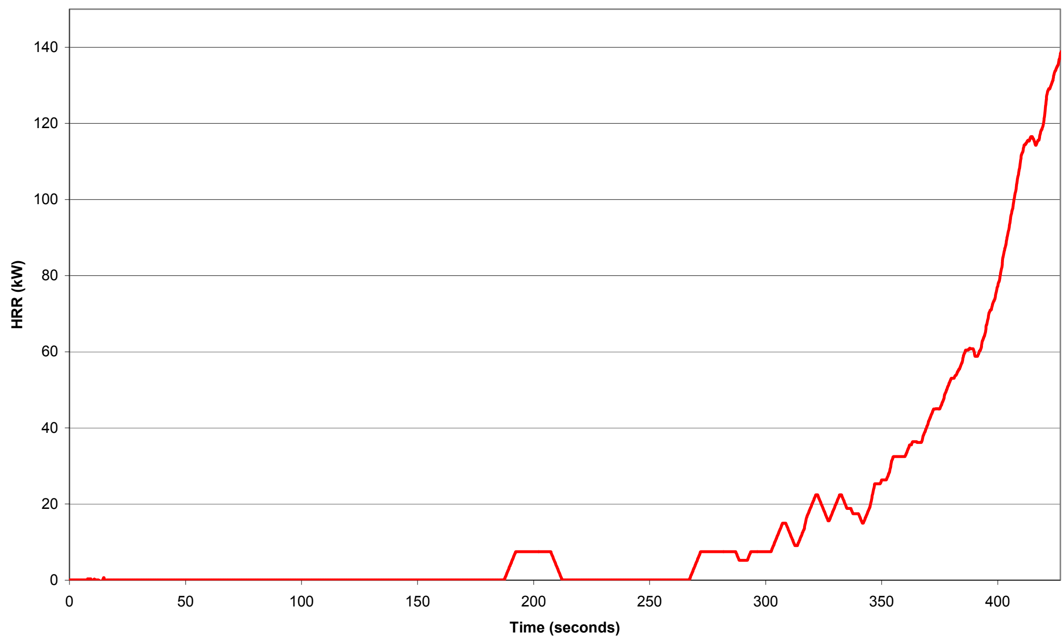

Figure I.8: Test 10 – Heat release rate

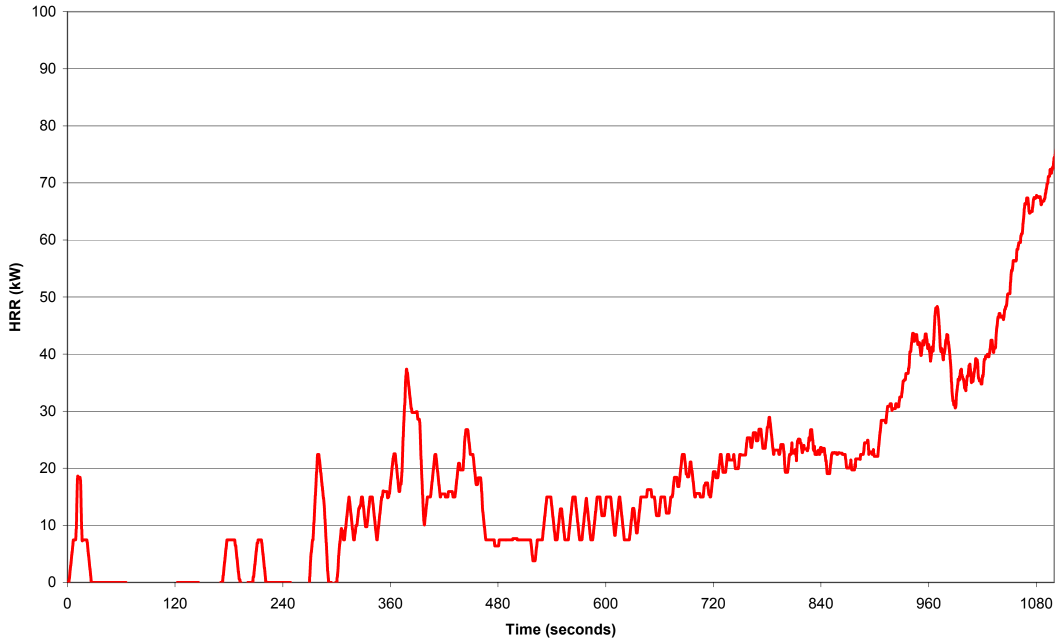

Figure I.9: Test 11 – Heat release rate

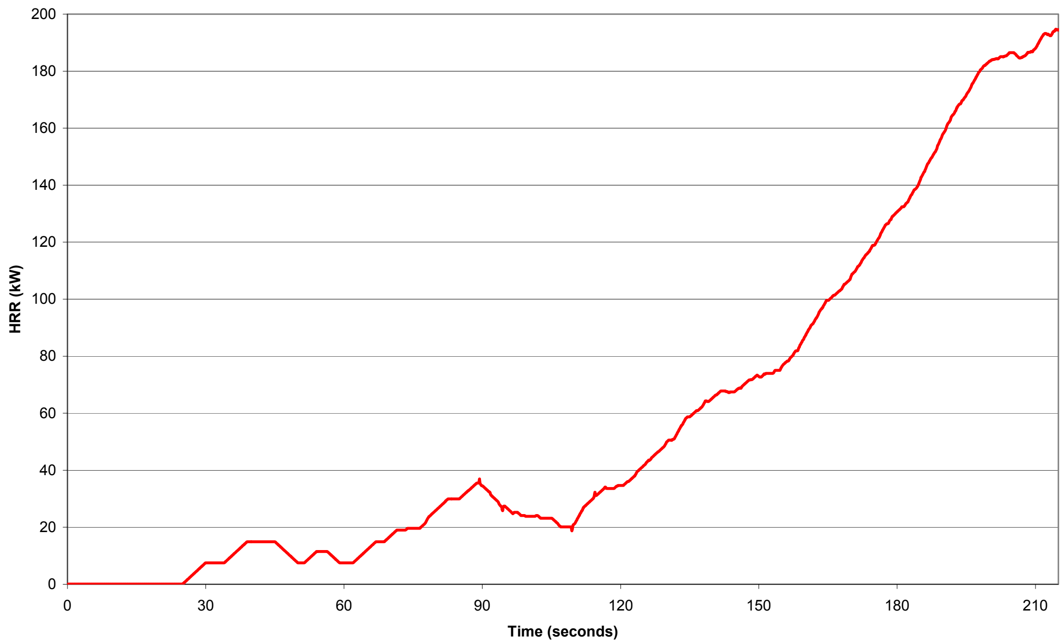

Figure I.10: Test 12 – Heat release rate

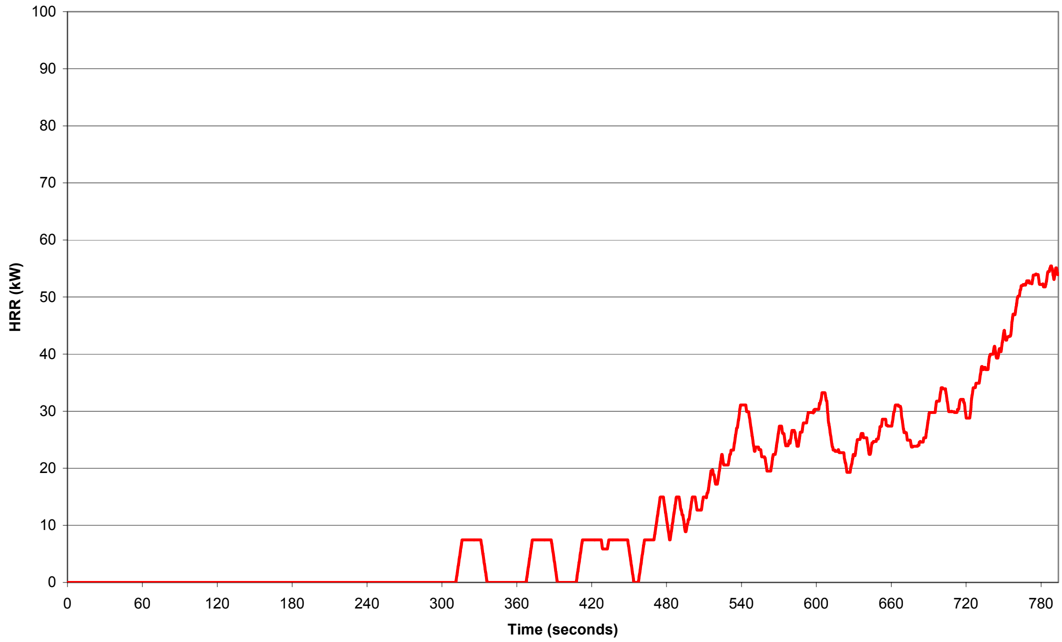

Figure I.11: Test 13 – Heat release rate

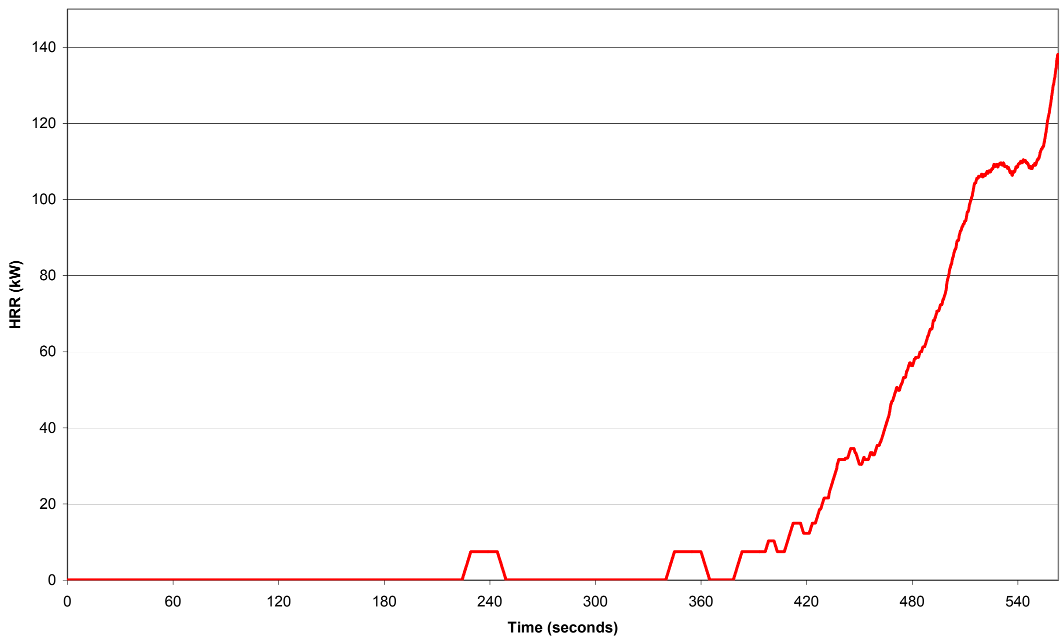

Figure I.12: Test 14 – Heat release rate

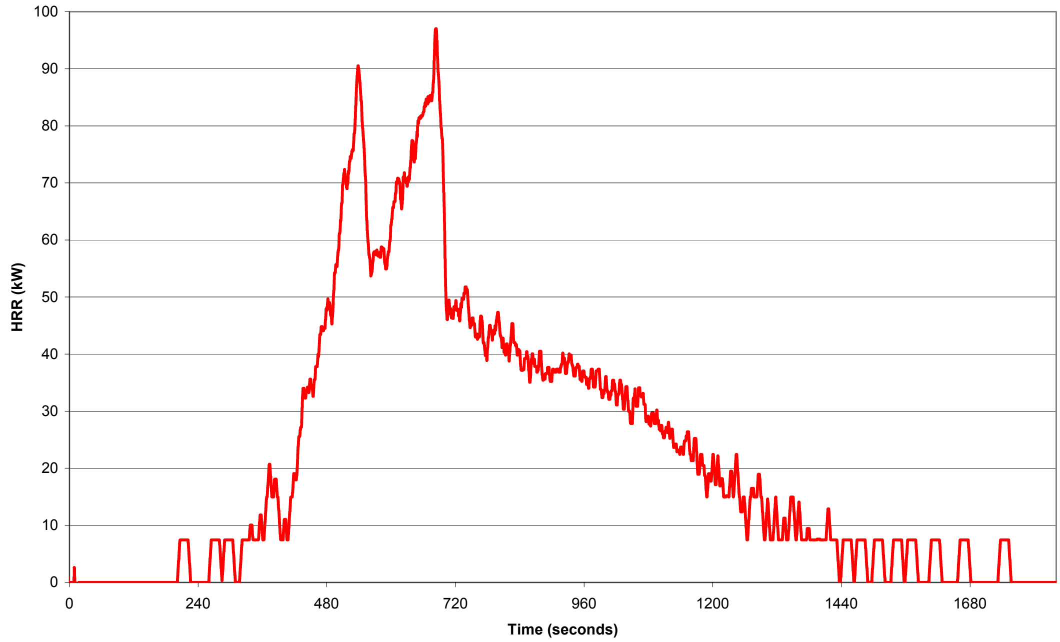

Figure I.13: Test 15 – Heat release rate

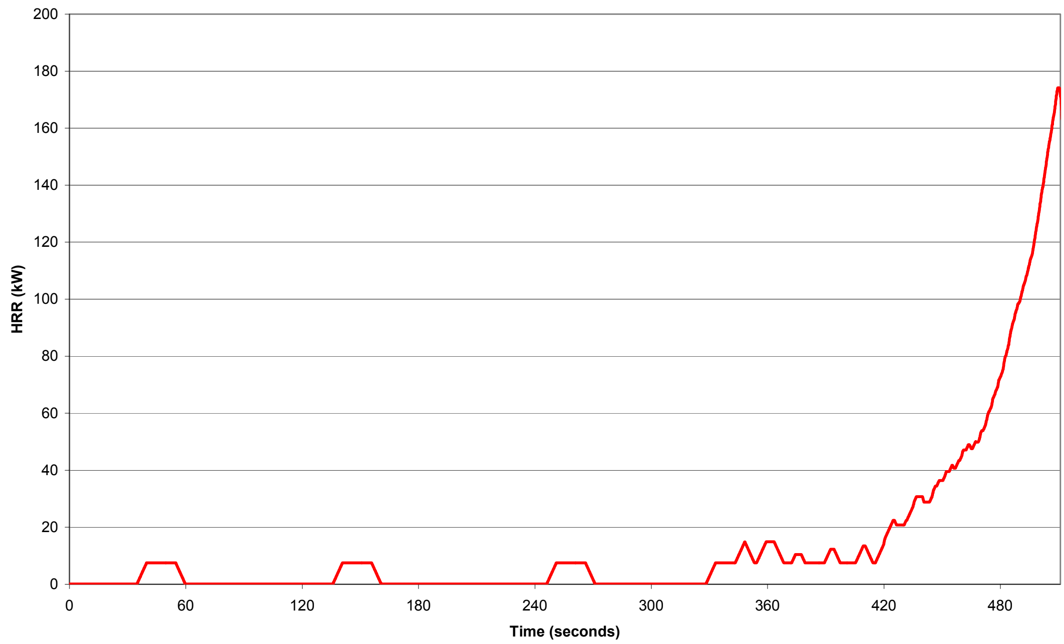

Figure I.14: Test 16 – Heat release rate

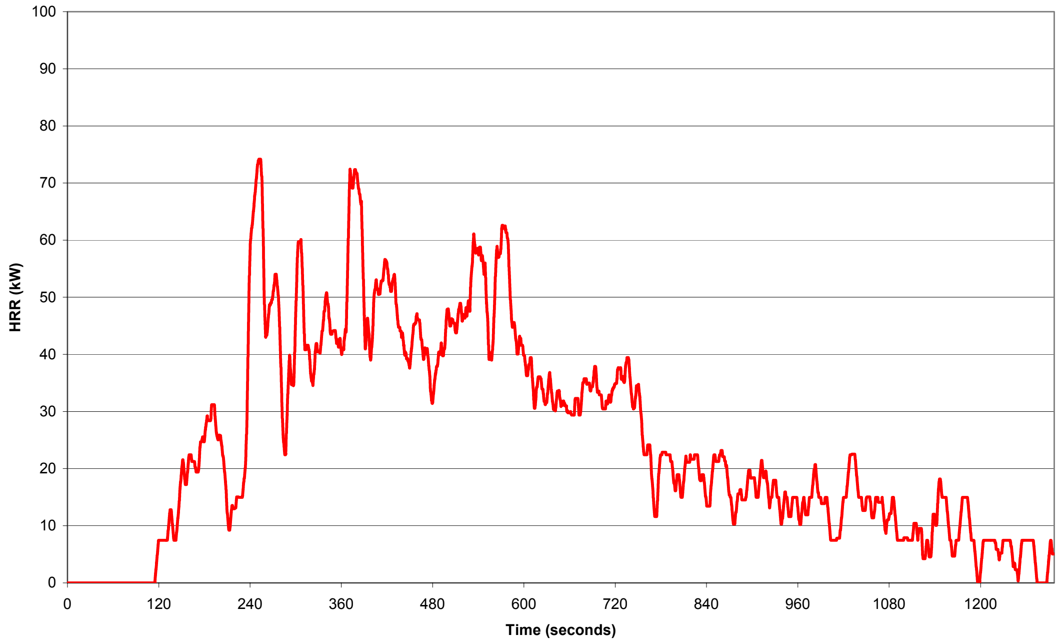

Figure I.15: Test 17 – Heat release rate

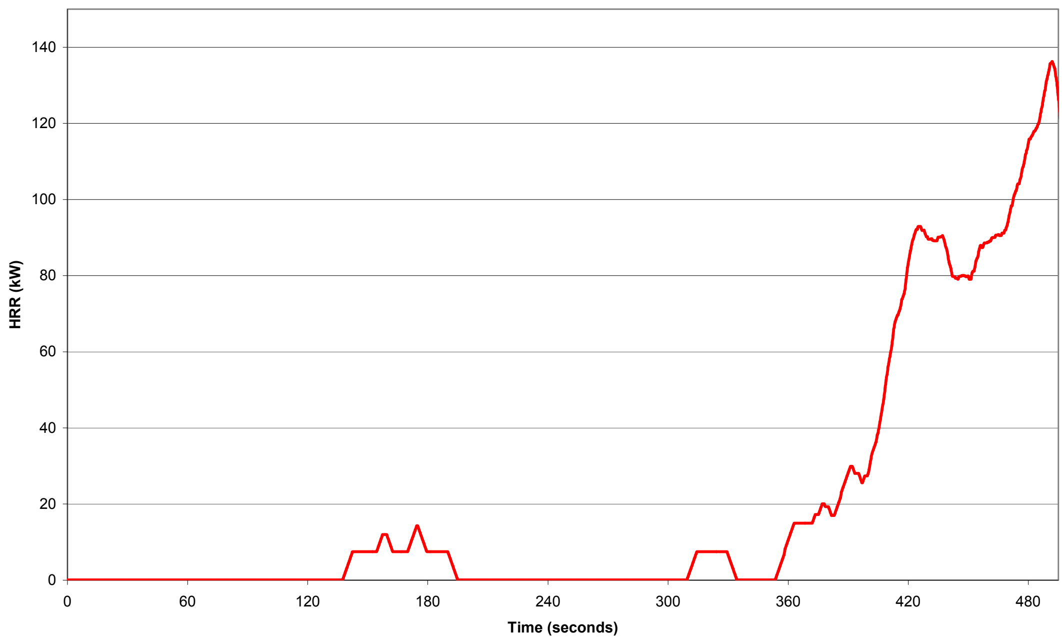

Figure I.16: Test 18 – Heat release rate

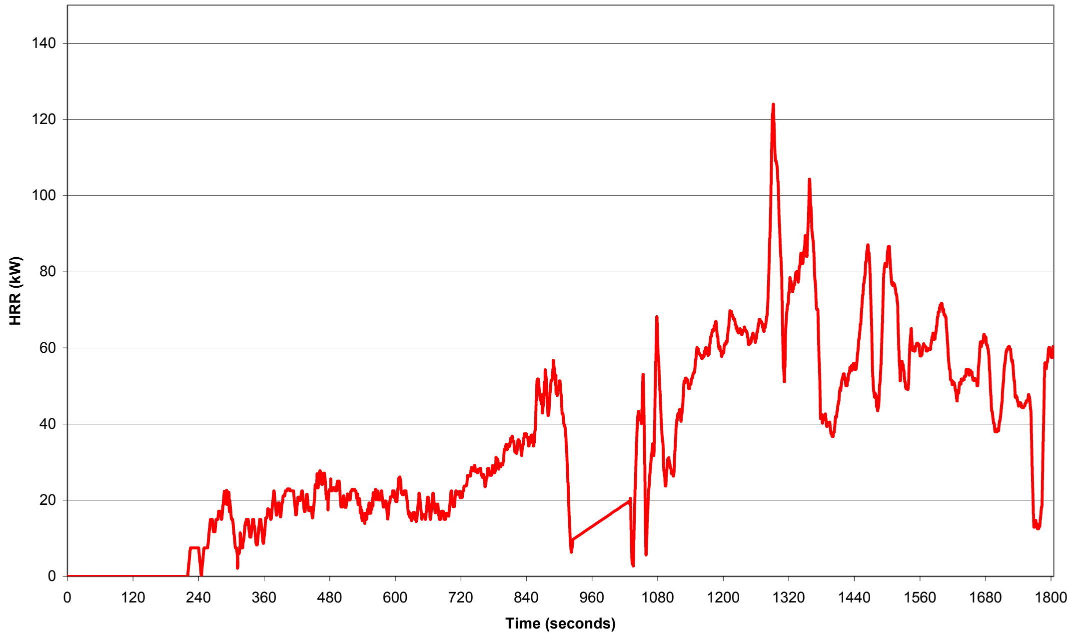

Figure I.17: Test 20 – Heat release rate

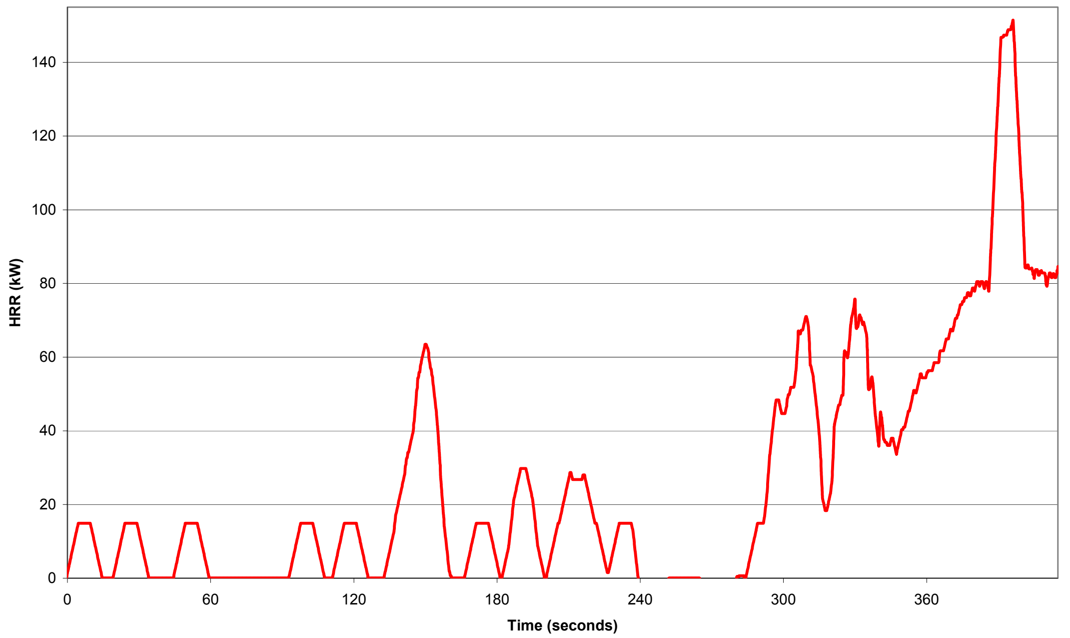

Figure I.18: Test 21 – Heat release rate

Appendix J Fractional Effective Dose

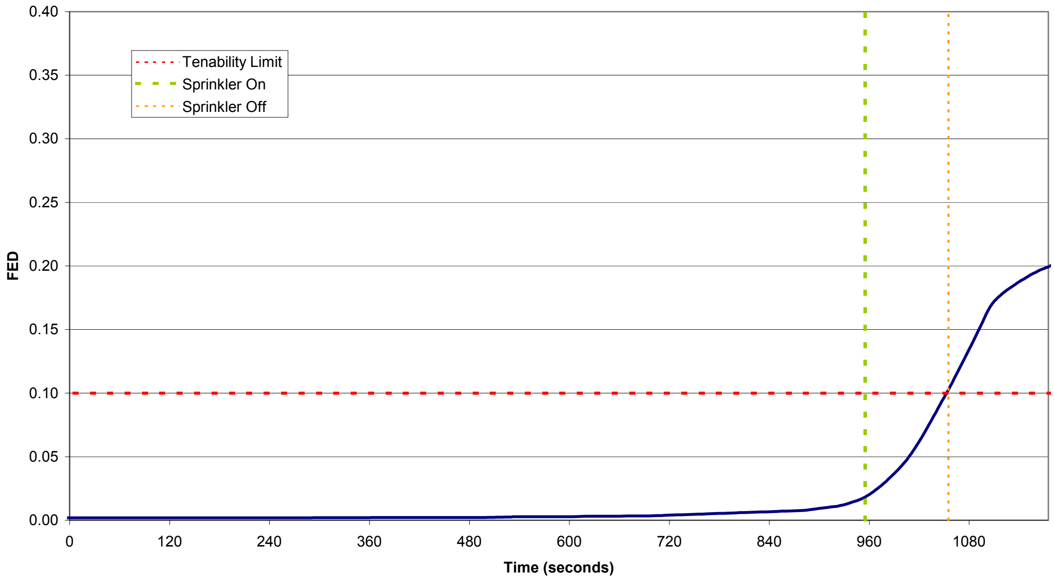

Figure J.1: Test 1 – FED$_{asphyxiant}$ (800 mm sampling height)

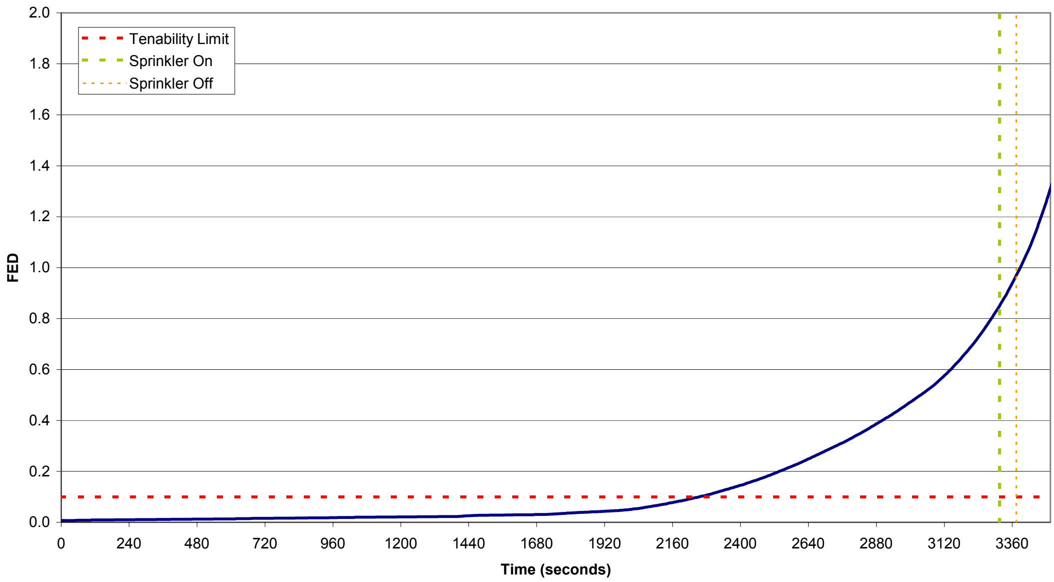

Figure J.2: Test 2 – FED$_{asphyxiant}$ (800 mm sampling height)

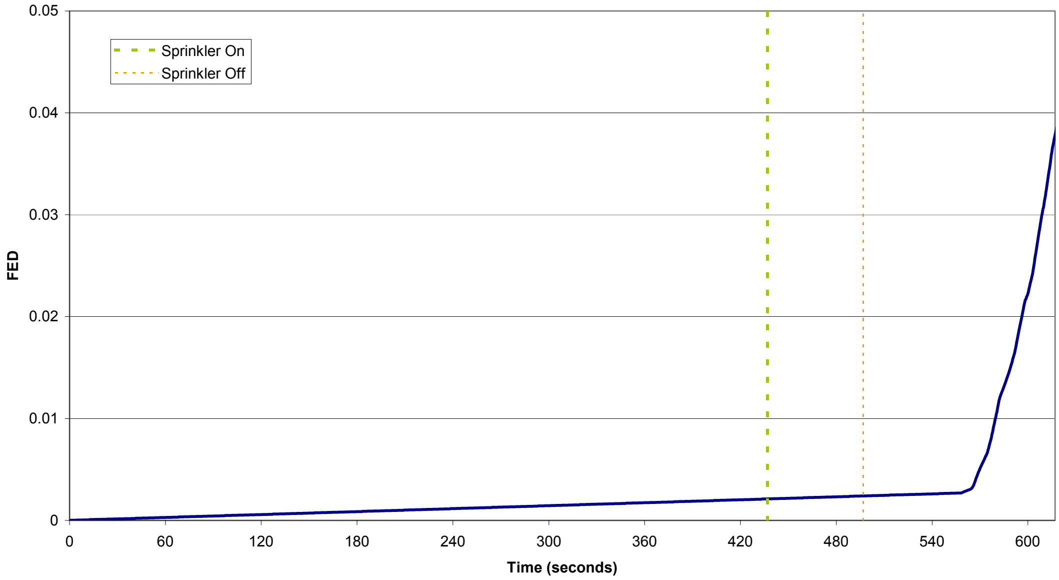

Figure J.3: Test 3 – FED$_{asphyxiant}$ (800 mm sampling height)

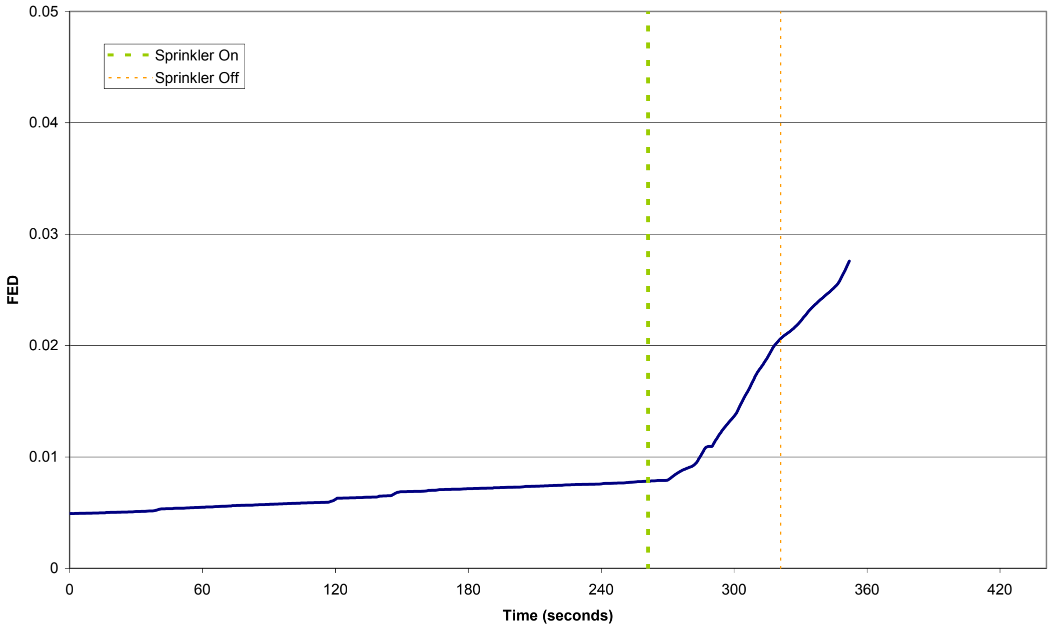

Figure J.4: Test 4 – FED$_{asphyxiant}$ (800 mm sampling height)

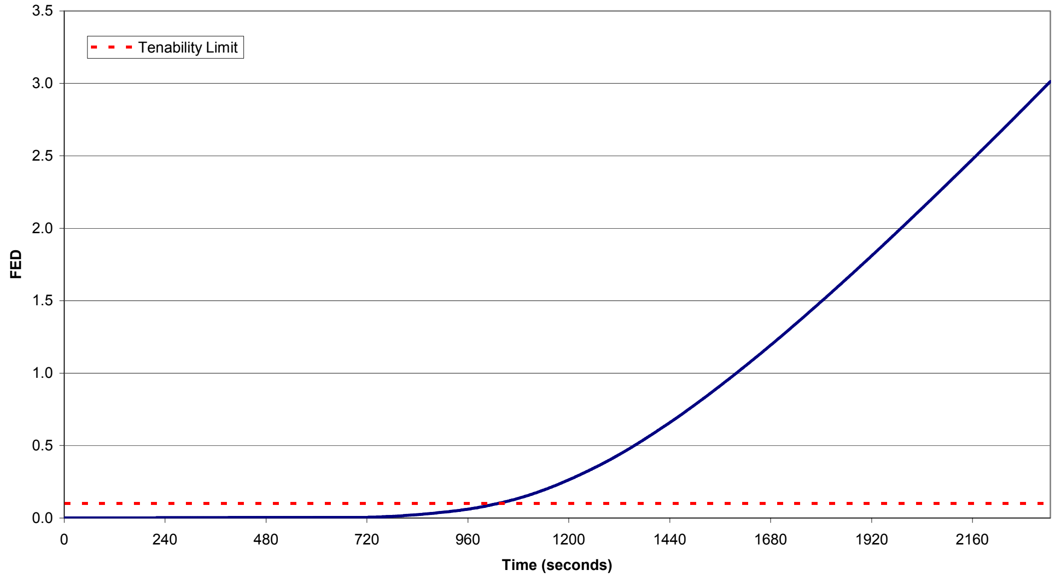

Figure J.5: Test 5 – FED$_{asphyxiant}$ (800 mm sampling height)

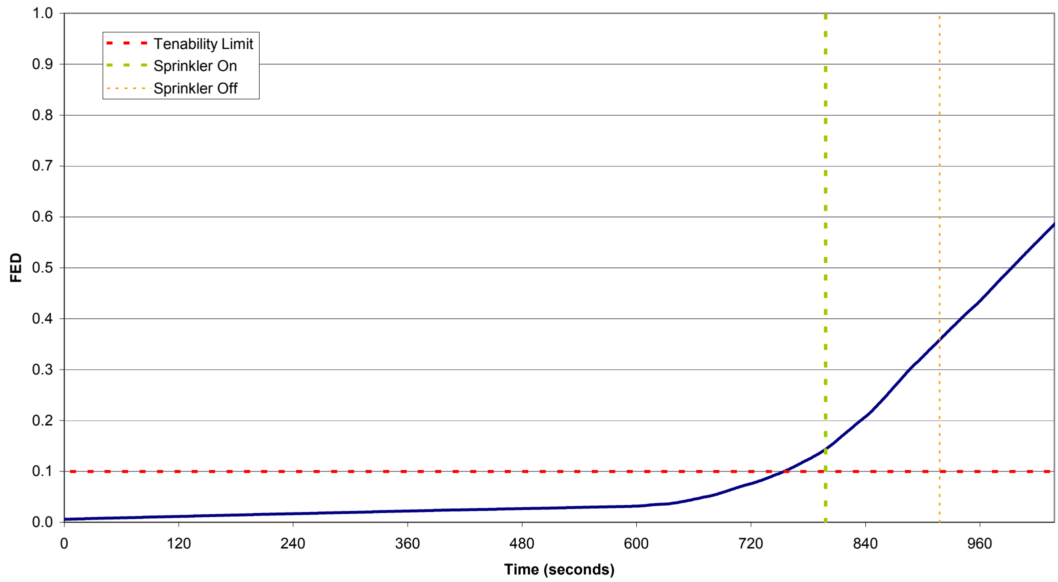

Figure J.6: Test 6 – FED$_{asphyxiant}$ (800 mm sampling height)

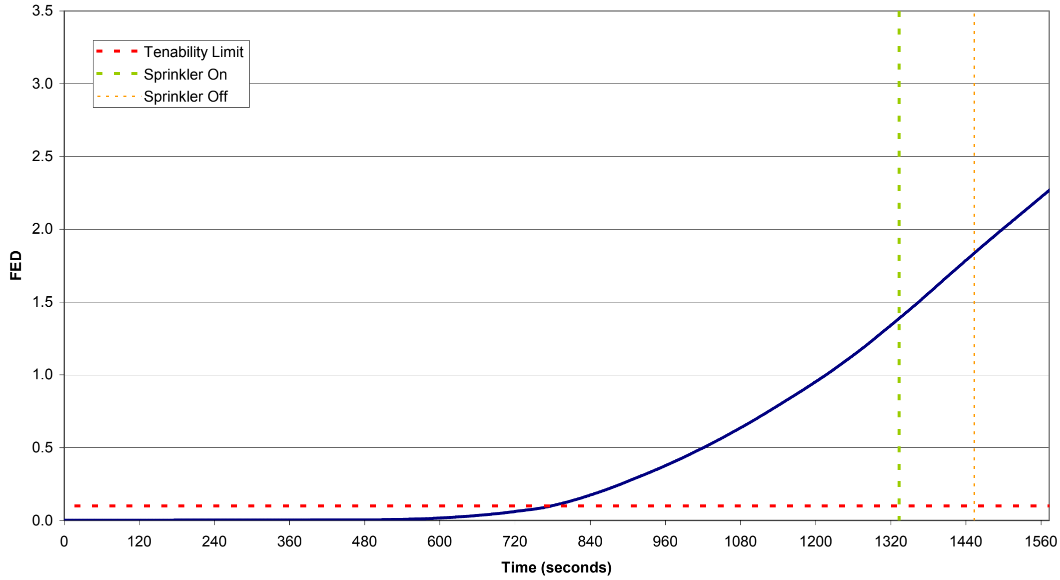

Figure J.7: Test 7 – $FED_{asphyxiant}$ (800 mm sampling height)

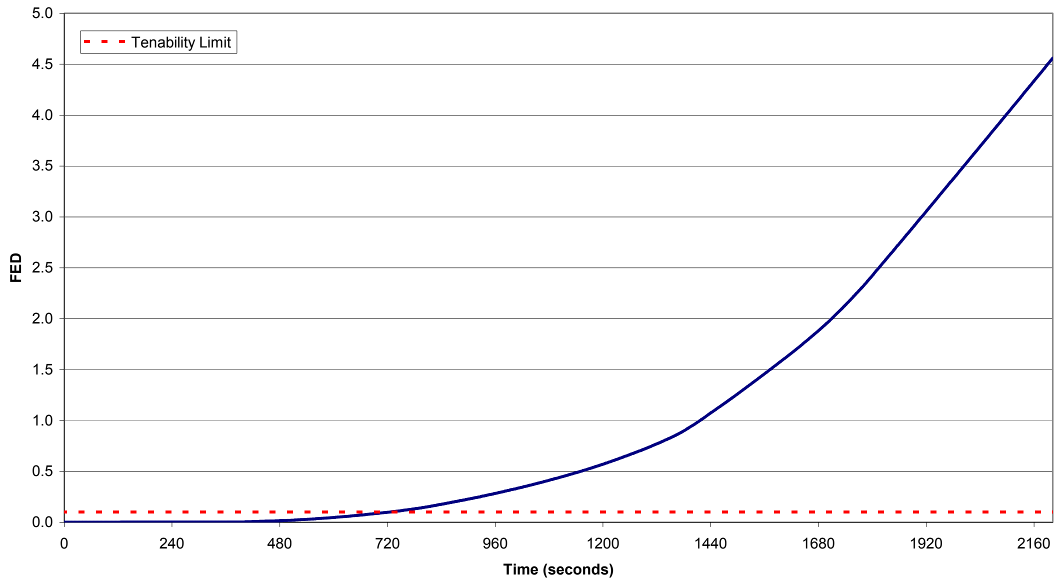

Figure J.8: Test 8 – $FED_{asphyxiant}$ (800 mm sampling height)

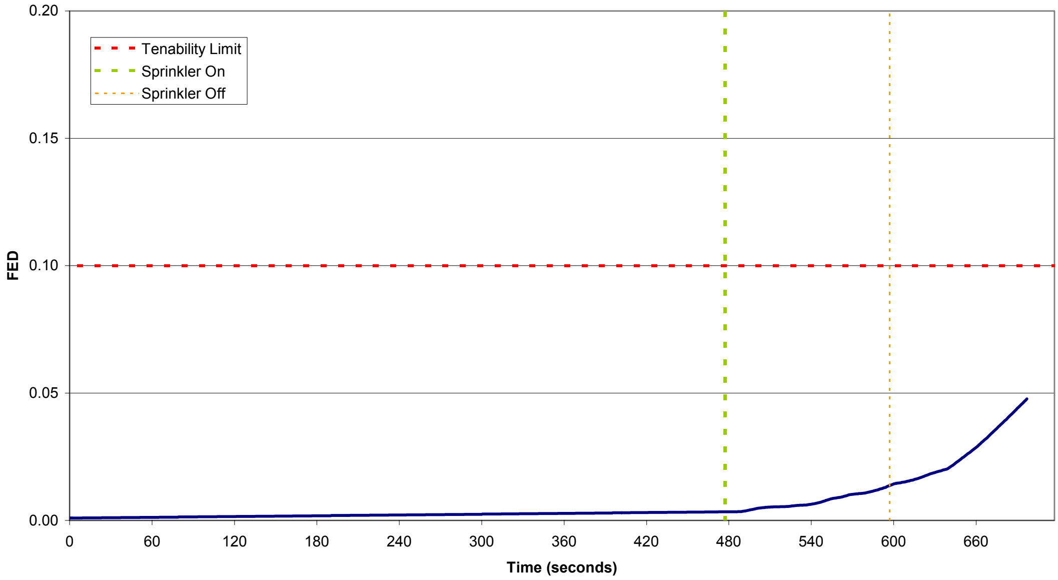

Figure J.9: Test 9 – FED$_{asphyxiant}$ (800 mm sampling height)

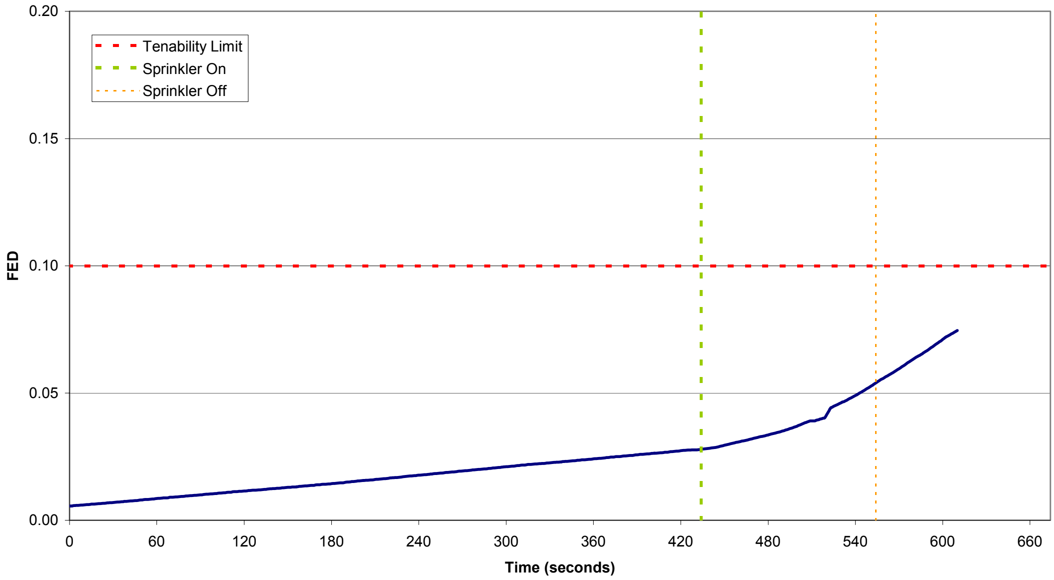

Figure J.10: Test 10 – FED$_{asphyxiant}$ (800 mm sampling height)

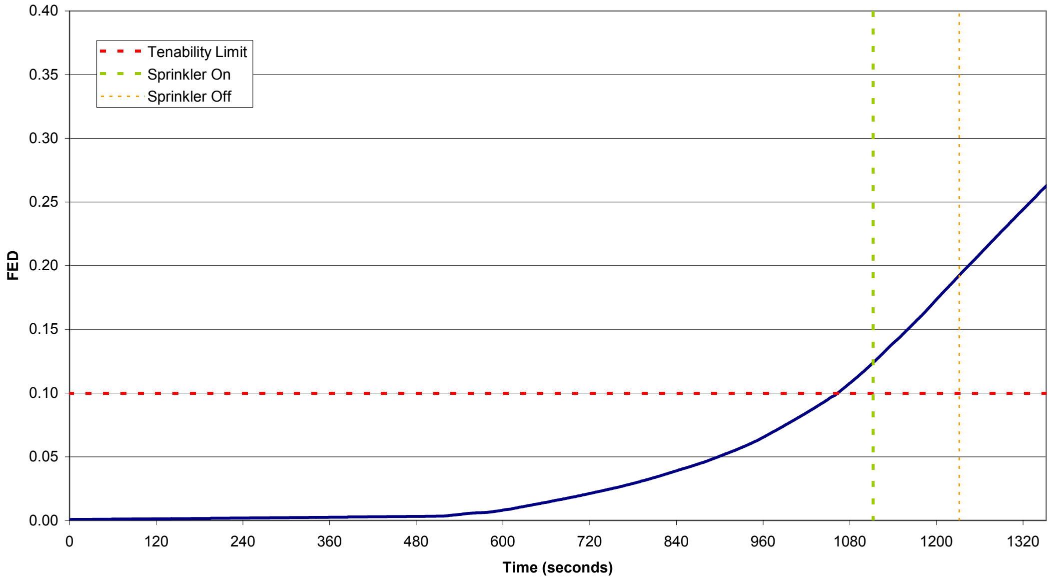

Figure J.11: Test 11 – FED$_{asphyxiant}$ (800 mm sampling height)

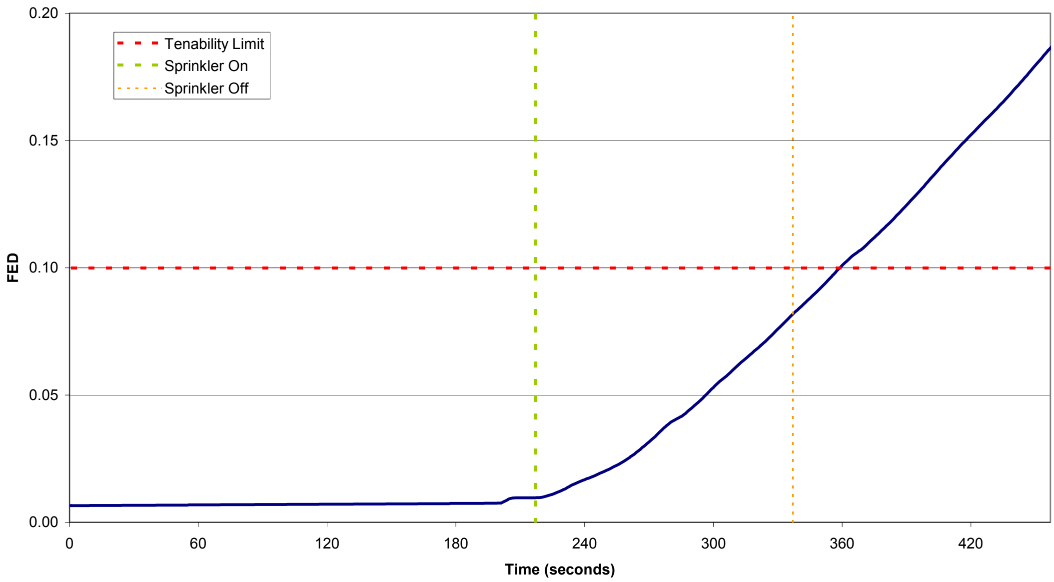

Figure J.12: Test 12 – FED$_{asphyxiant}$ (800 mm sampling height)

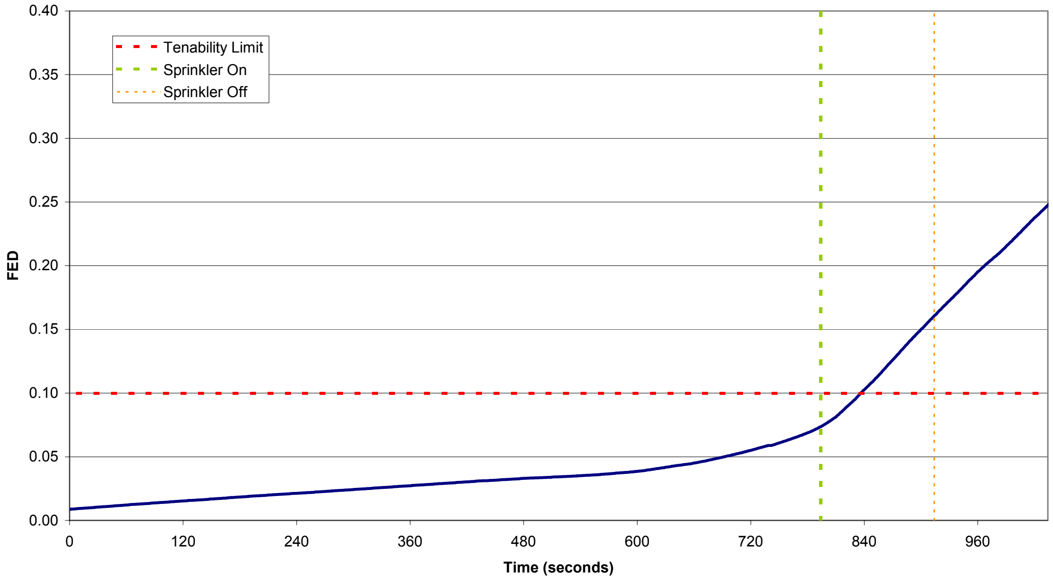

Figure J.13: Test 13 – FED$_{asphyxiant}$ (800 mm sampling height)

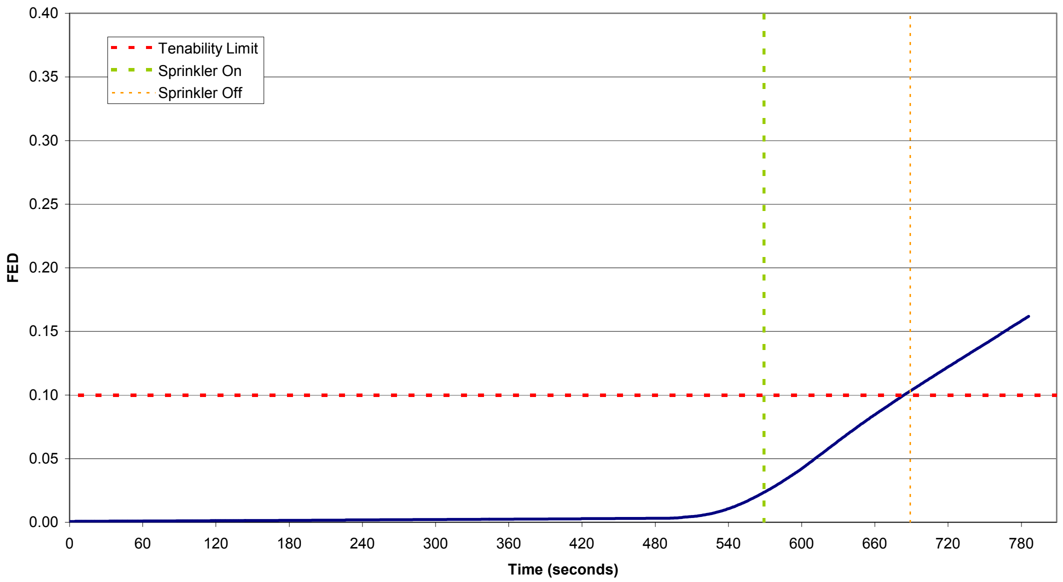

Figure J.14: Test 14 – FED$_{asphyxiant}$ (1600 mm sampling height)

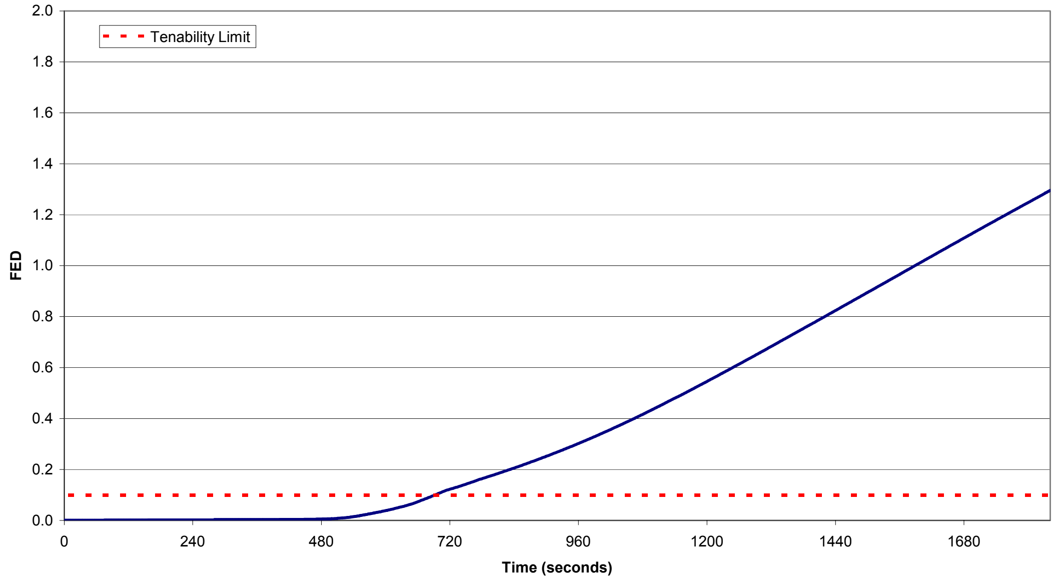

Figure J.15: Test 15 – FED$_{asphyxiant}$ (1600 mm sampling height)

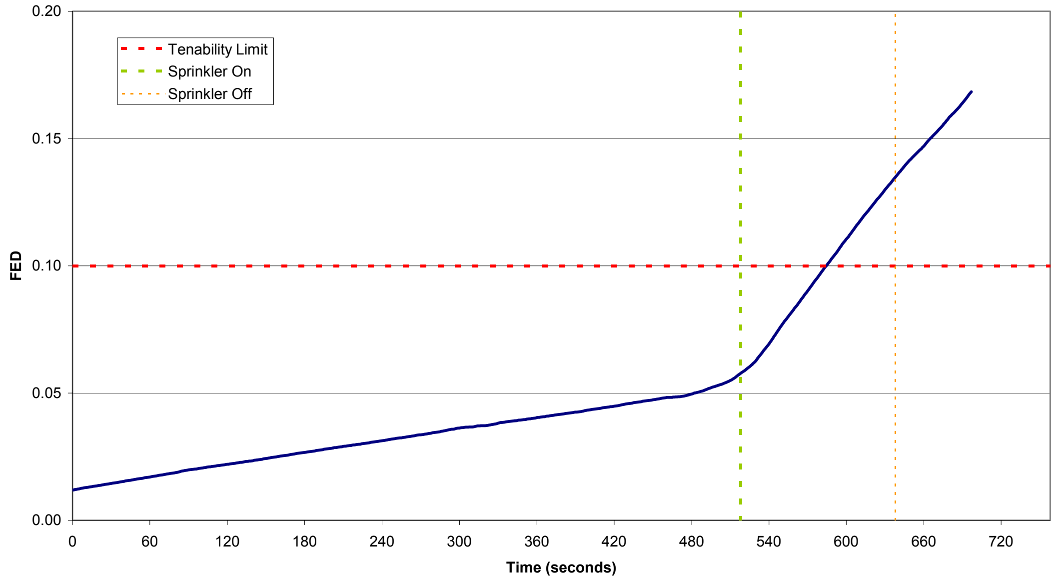

Figure J.16: Test 16 – FED$_{asphyxiant}$ (1600 mm sampling height)

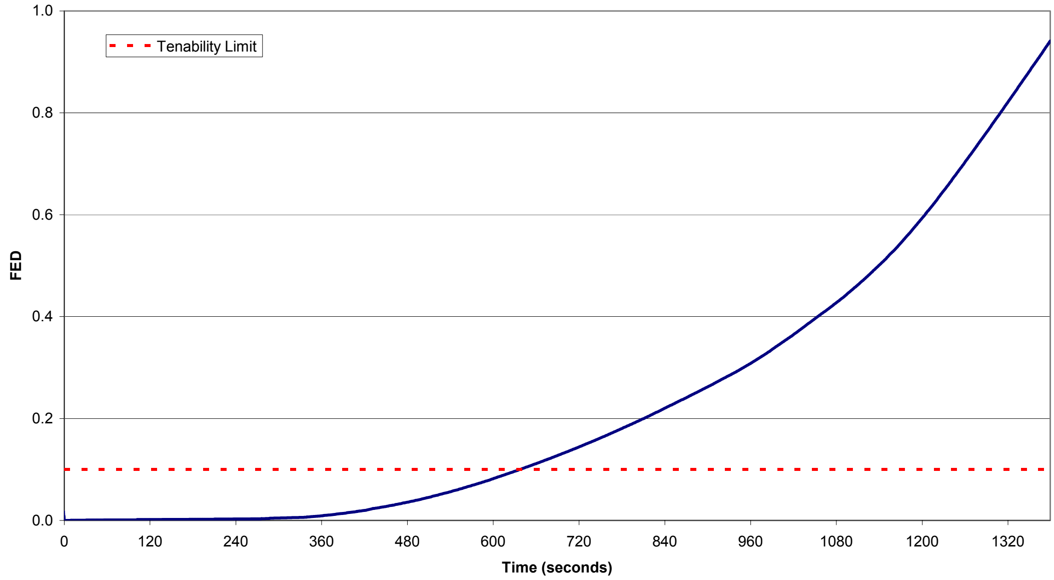

Figure J.17: Test 17 – FED$_{asphyxiant}$ (800 mm sampling height)

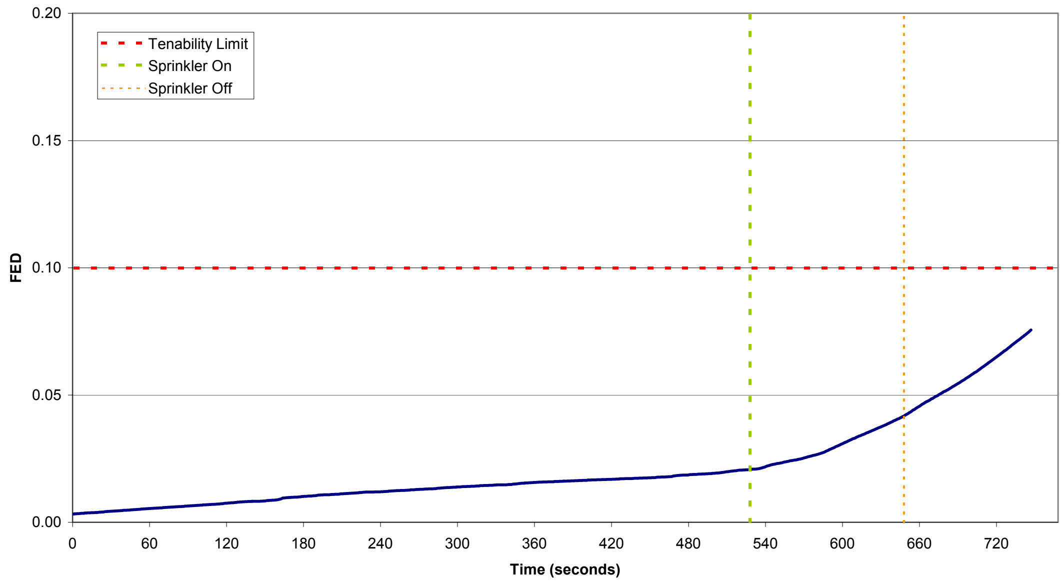

Figure J.18: Test 18 – FED$_{asphyxiant}$ (800 mm sampling height)

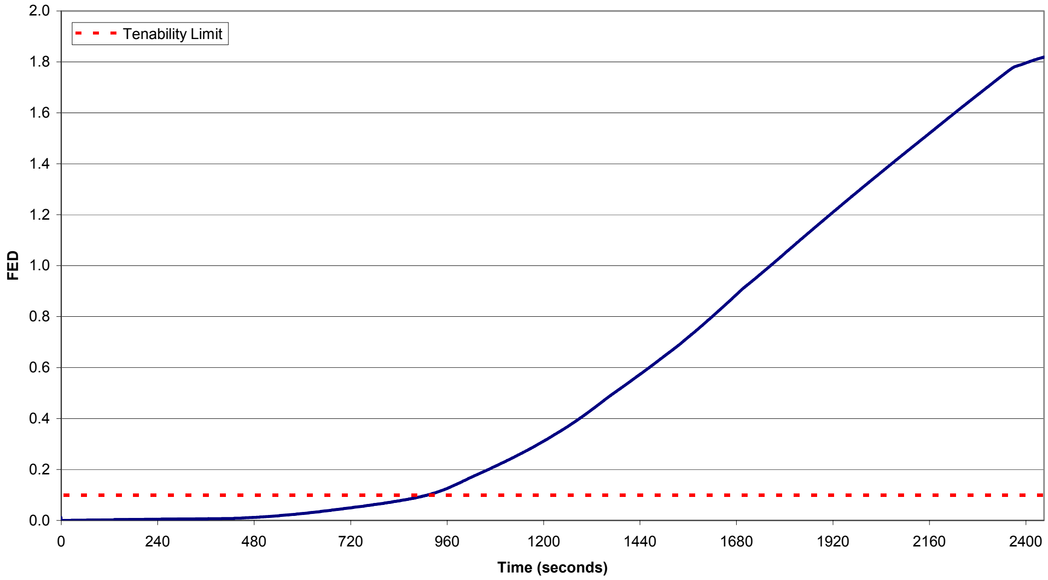

Figure J.19: Test 20 – FED$_{asphyxiant}$ (800 mm sampling height)

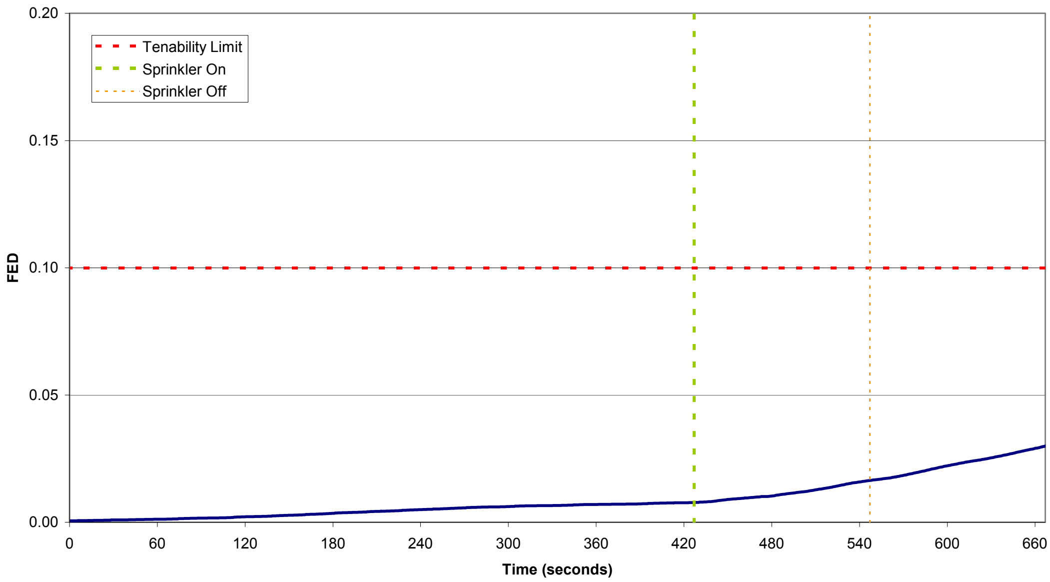

Figure J.20: Test 21 – FED$_{asphyxiant}$ (800 mm sampling height)

Appendix K Mass Loss

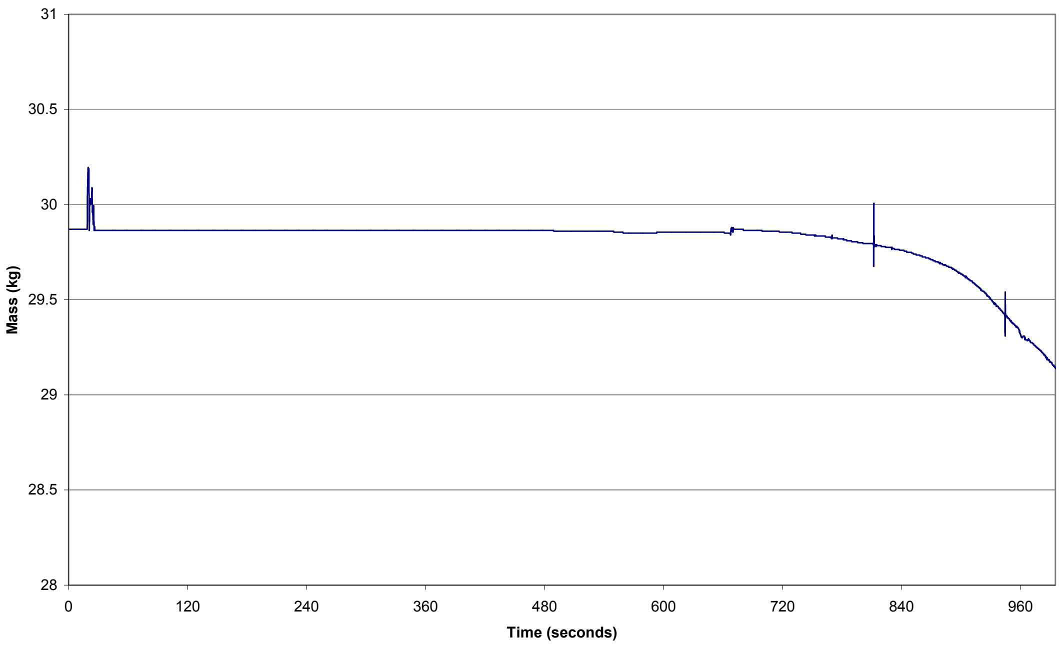

Figure K.1: Test 1 - Mass loss curve

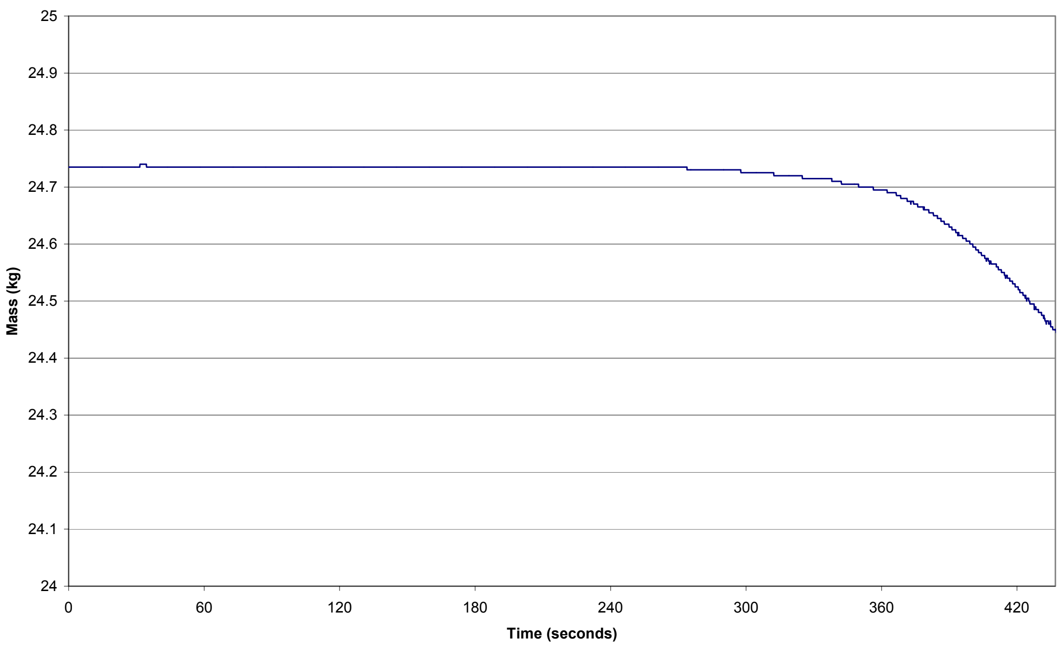

Figure K.2: Test 3 - Mass loss curve

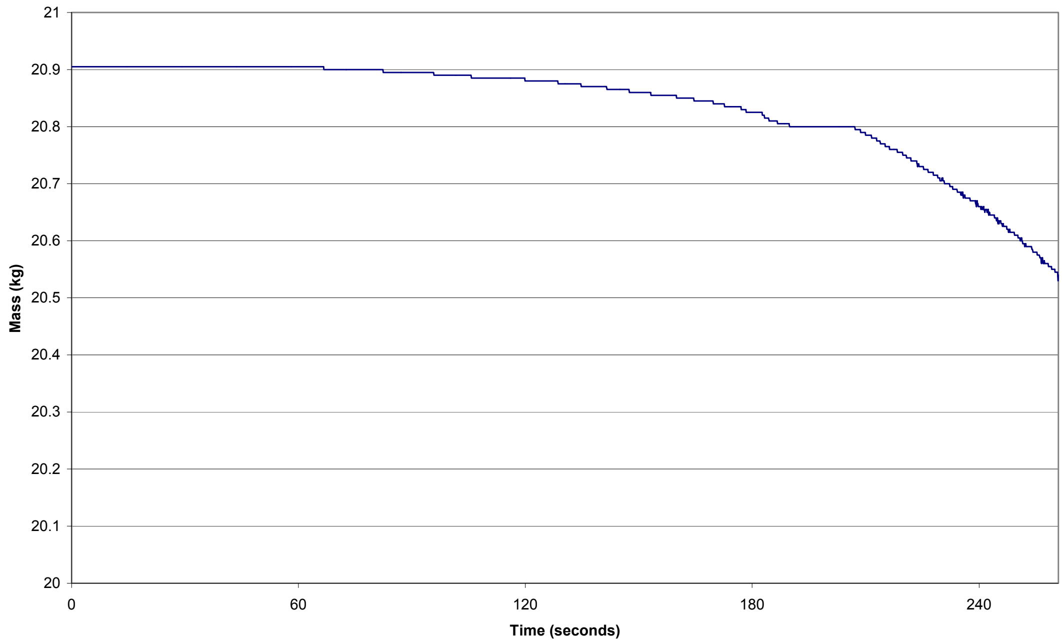

Figure K.3: Test 4 - Mass loss curve

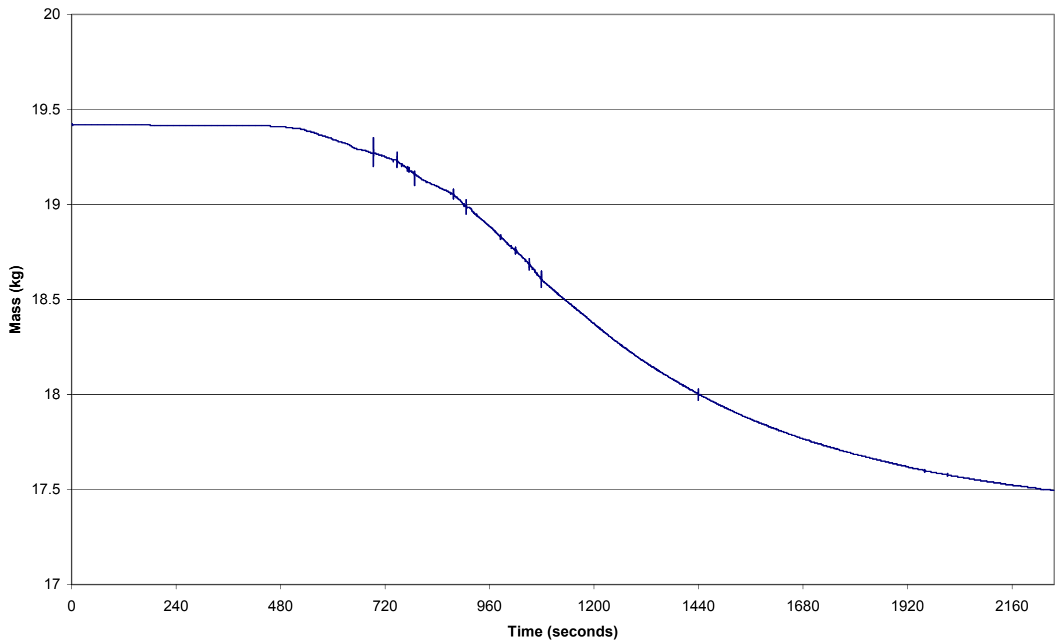

Figure K.4: Test 5 - Mass loss curve

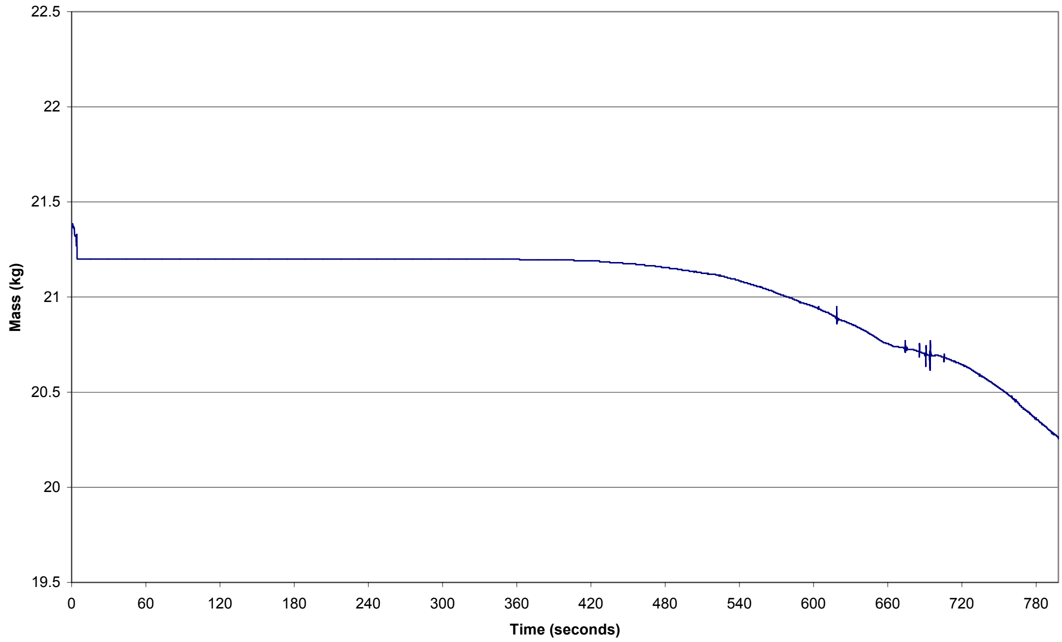

Figure K.5: Test 6 - Mass loss curve

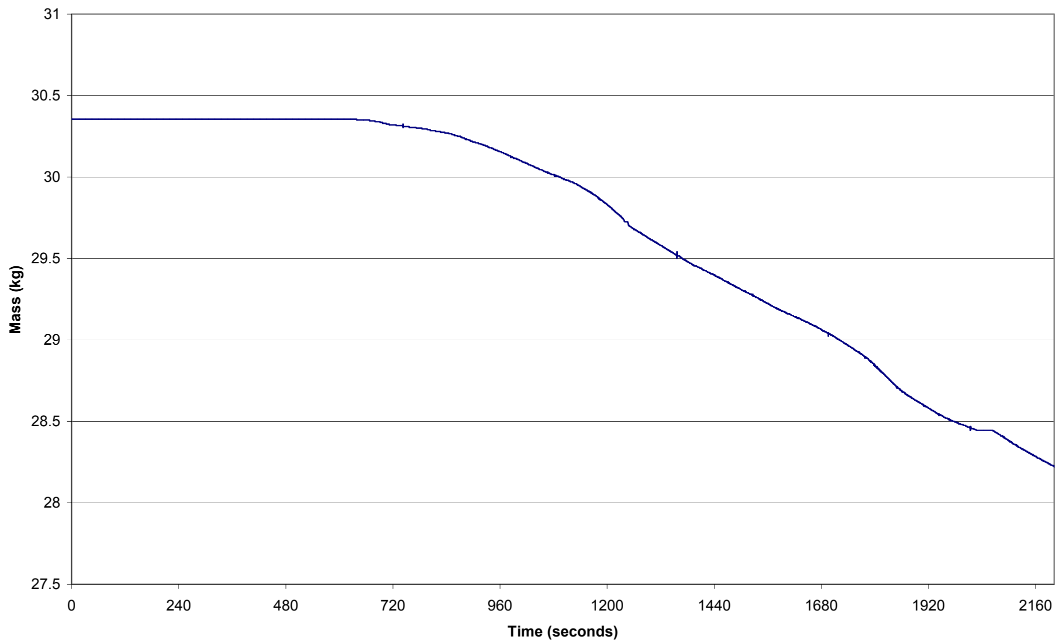

Figure K.6: Test 8 - Mass loss curve

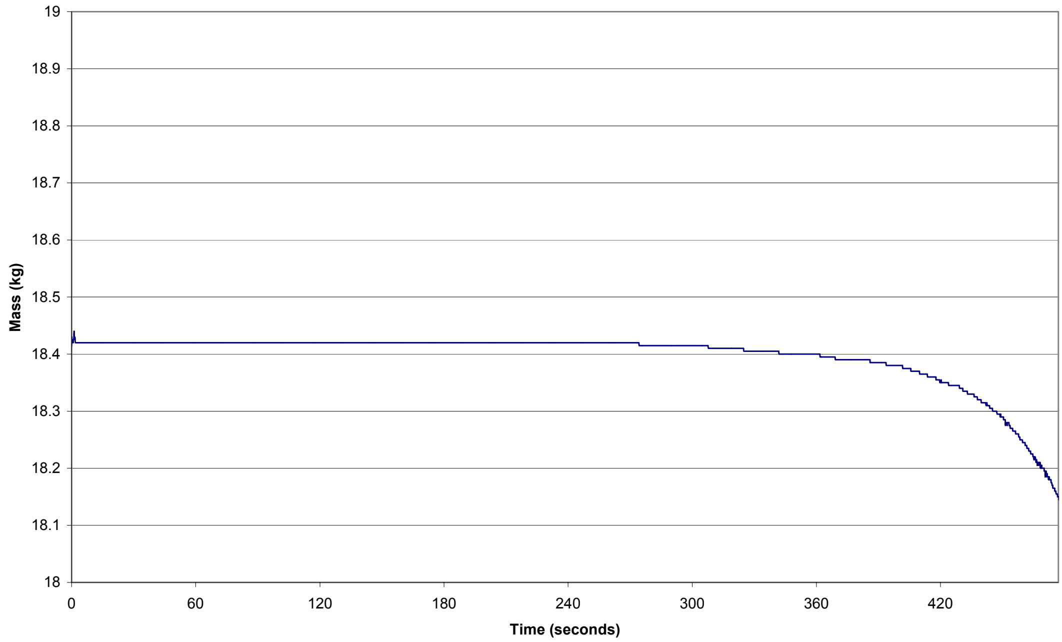

Figure K.7: Test 9 - Mass loss curve

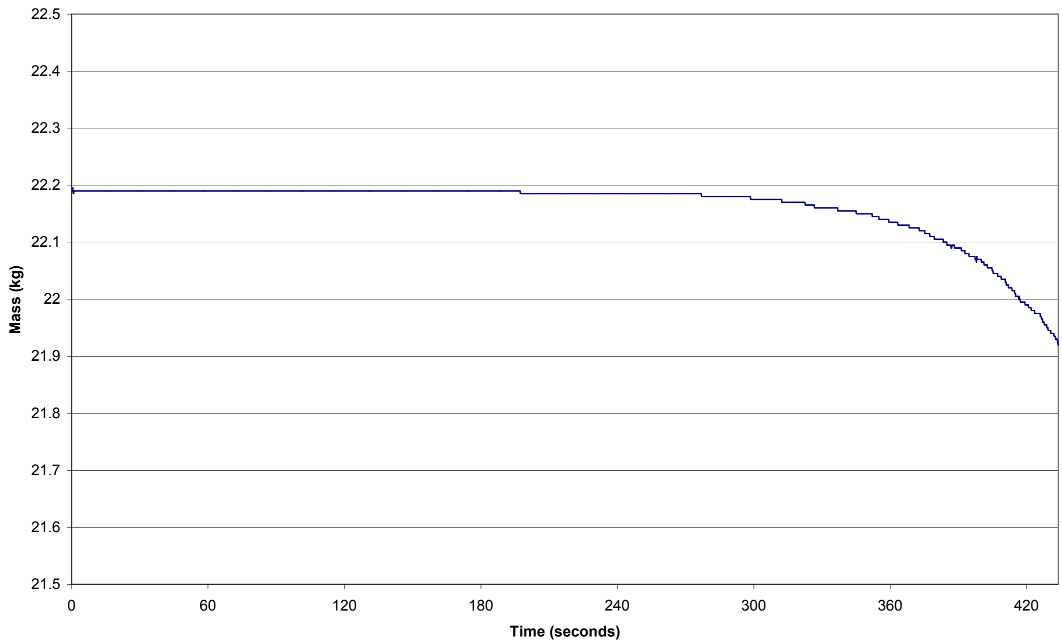

Figure K.8: Test 10 - Mass loss curve

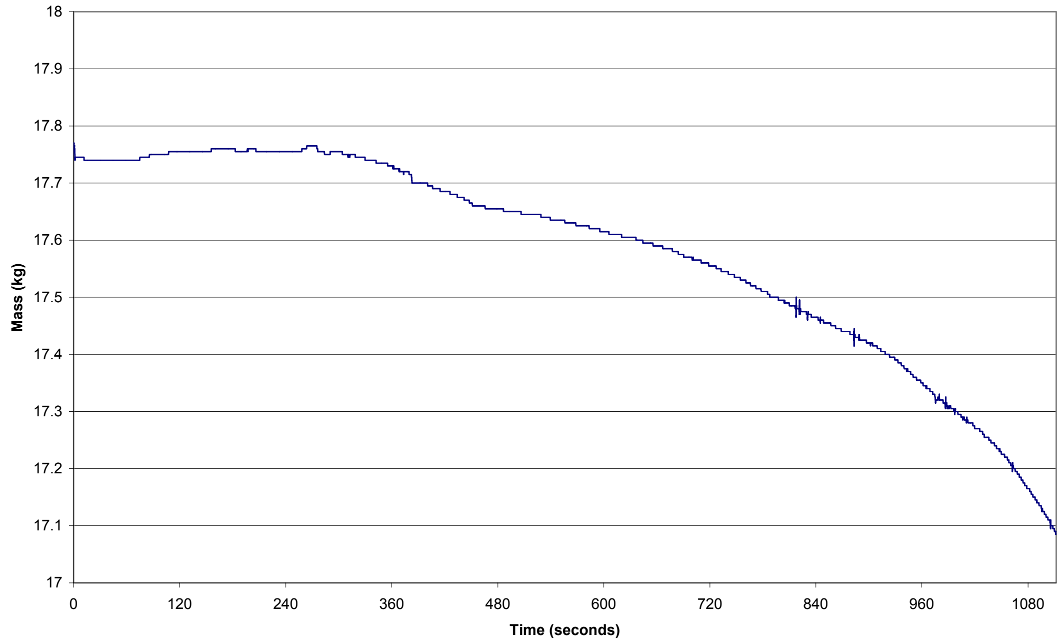

Figure K.9: Test 11 - Mass loss curve

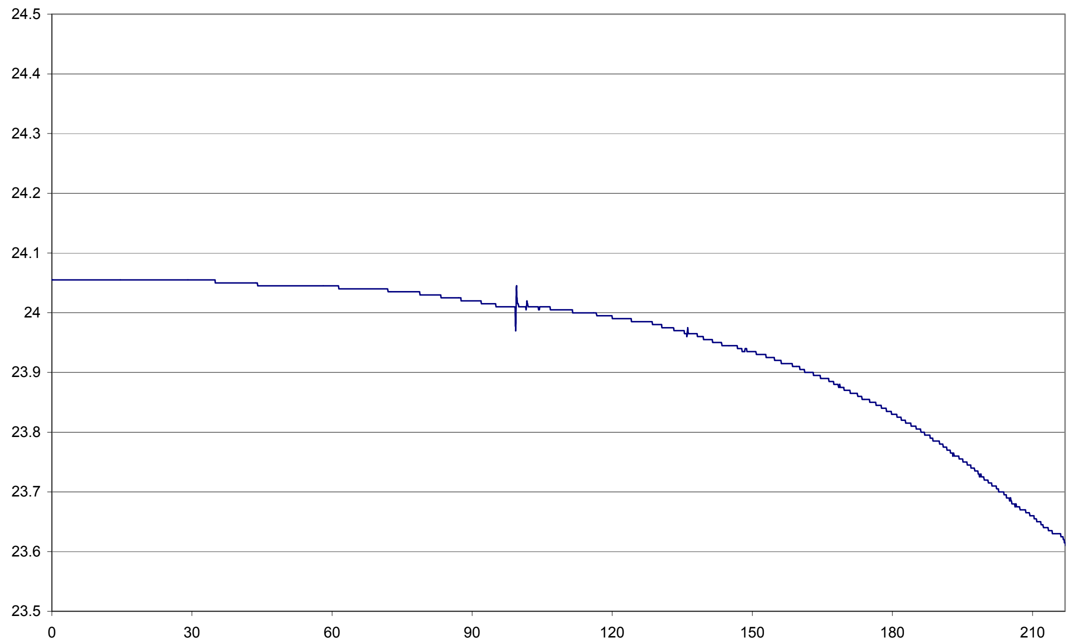

Figure K.10: Test 12 - Mass loss curve

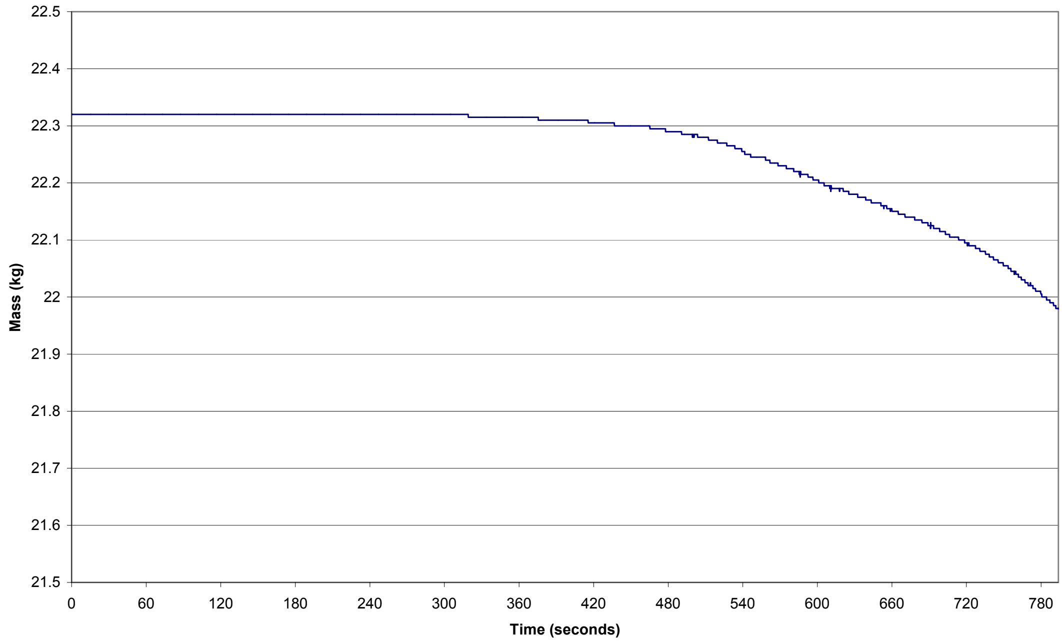

Figure K.11: Test 13 - Mass loss curve

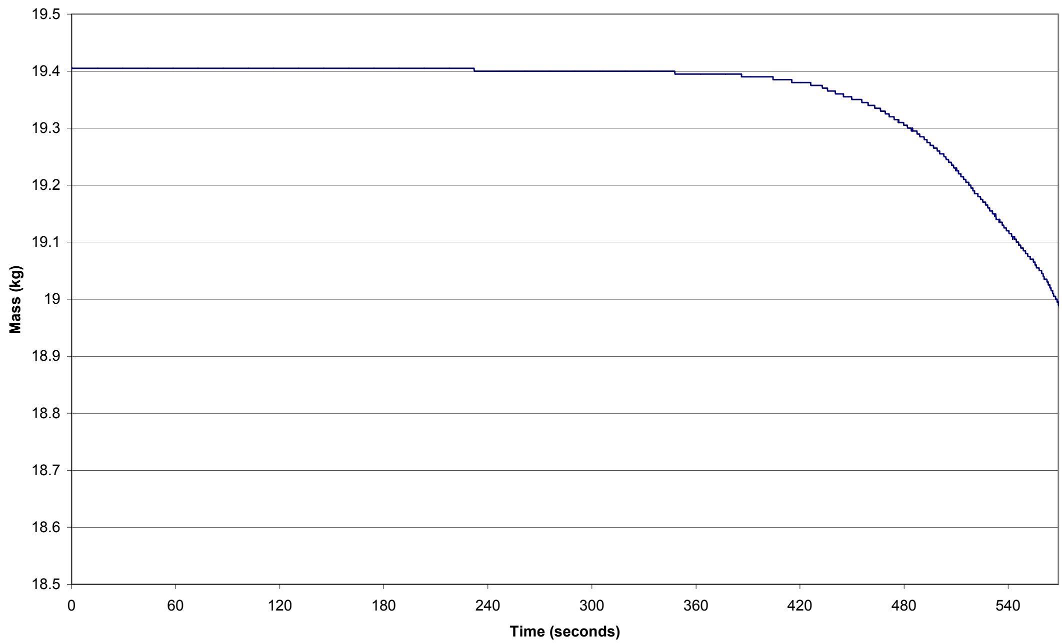

Figure K.12: Test 14 - Mass loss curve

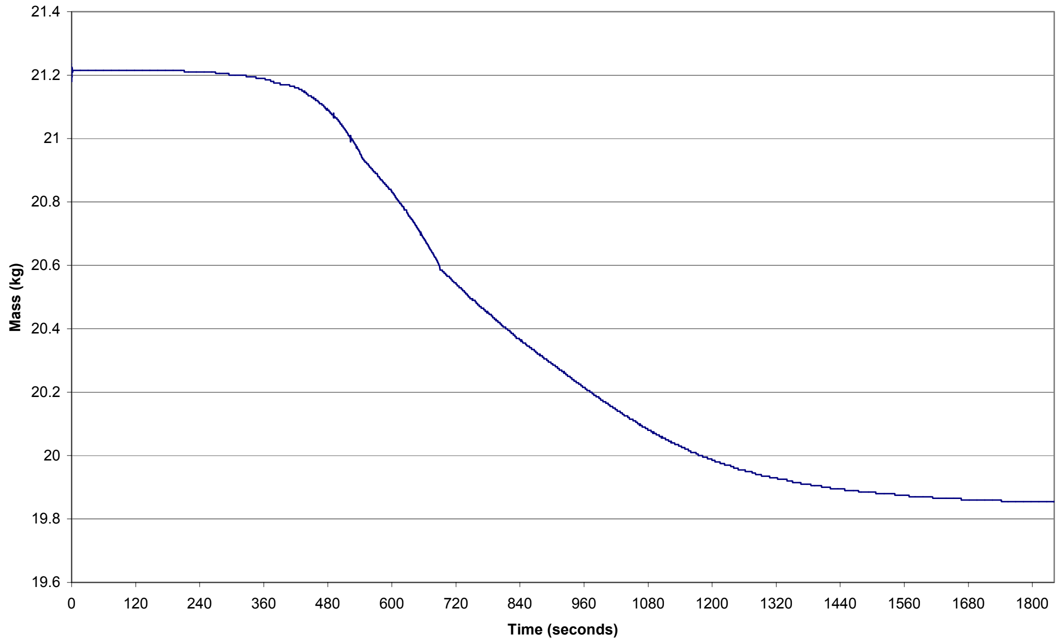

Figure K.13: Test 15 - Mass loss curve

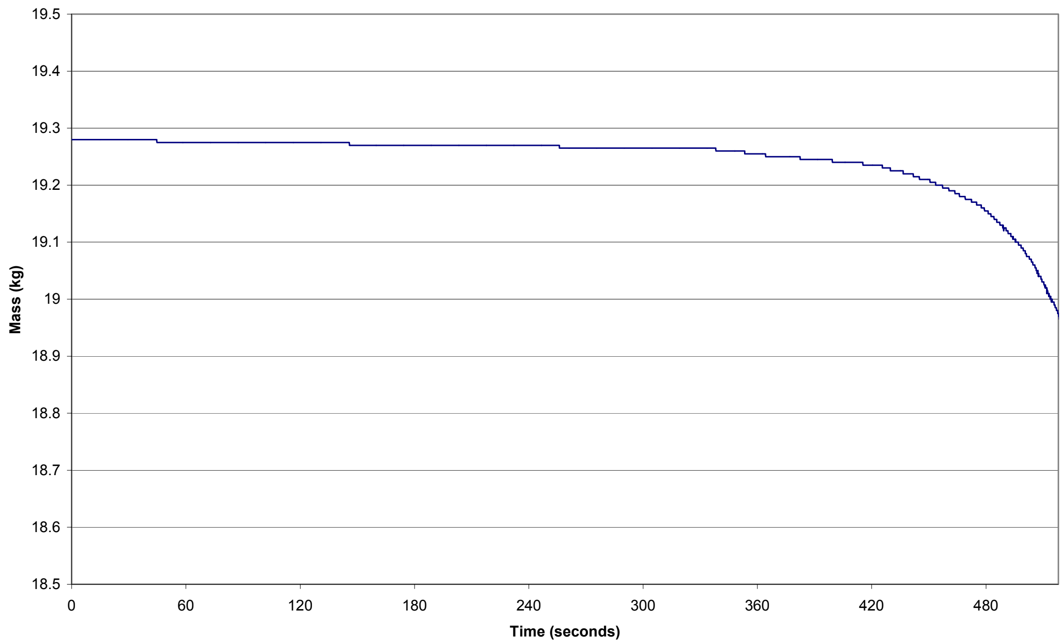

Figure K.14: Test 16 - Mass loss curve

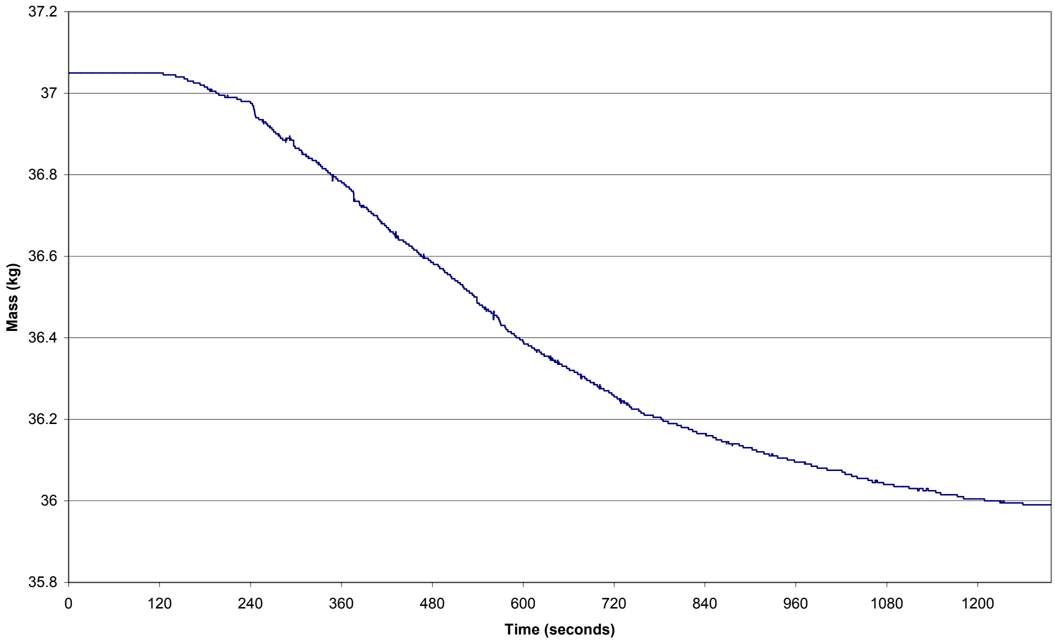

Figure K.15: Test 17 - Mass loss curve

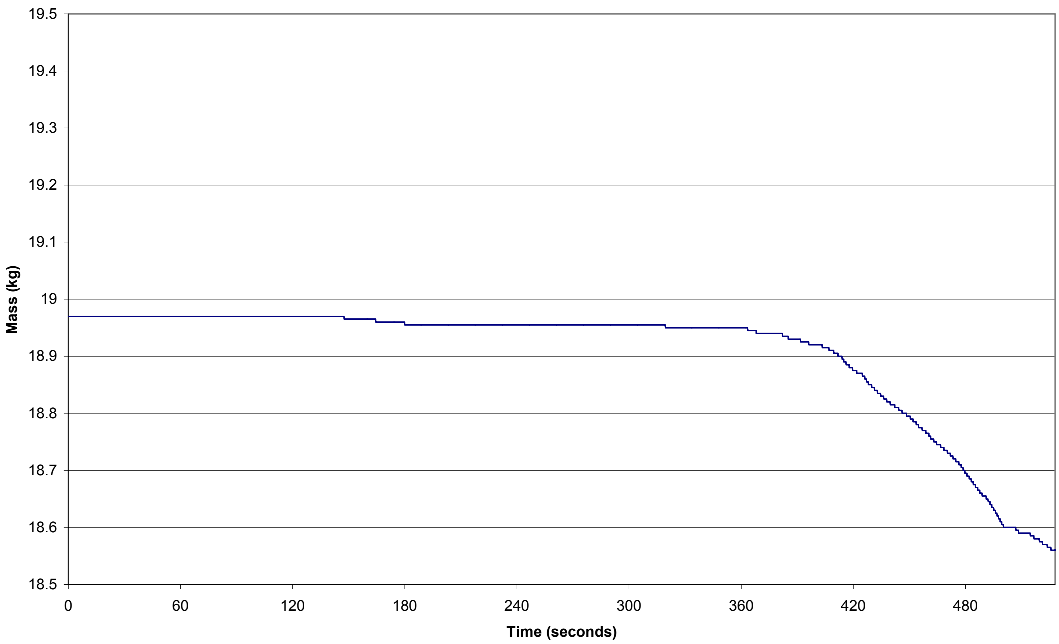

Figure K.16: Test 18 - Mass loss curve

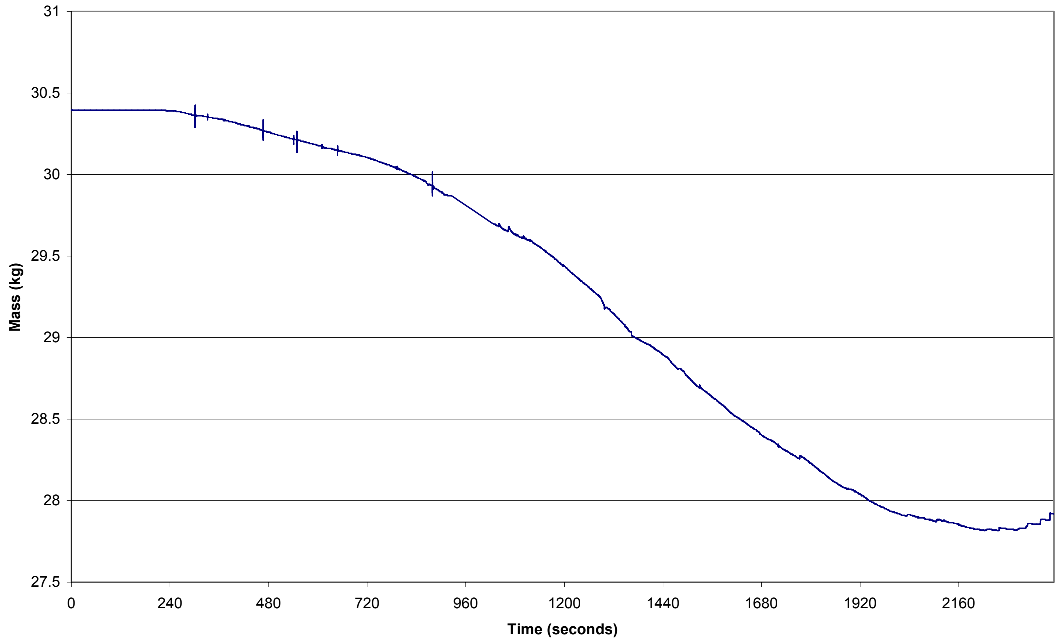

Figure K.17: Test 20 - Mass loss curve

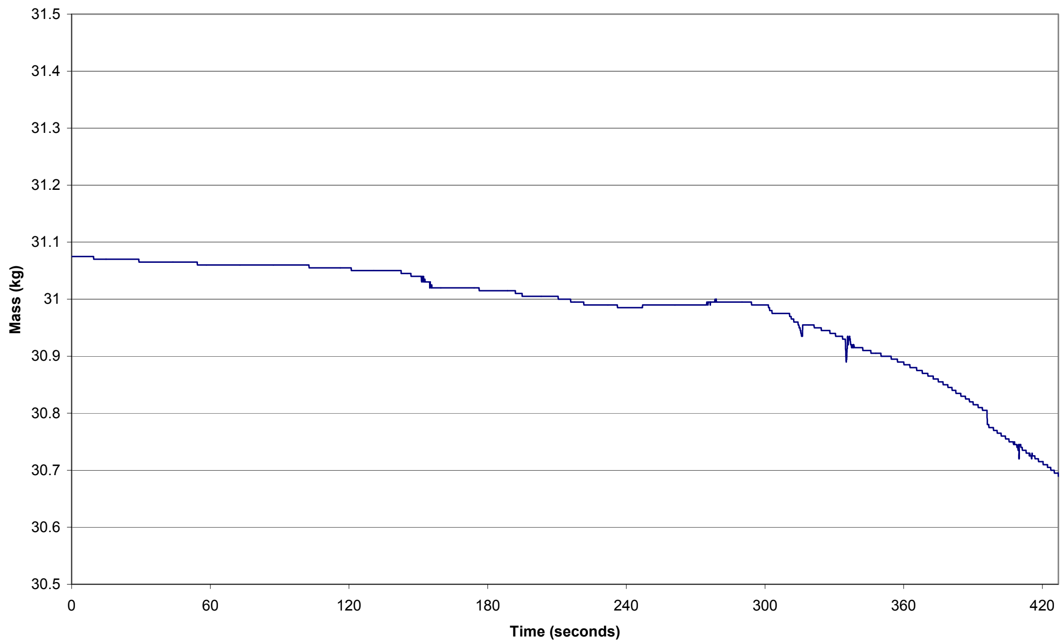

Figure K.18: Test 21 - Mass loss curve

Appendix L Alert Time vs Available Escape Time

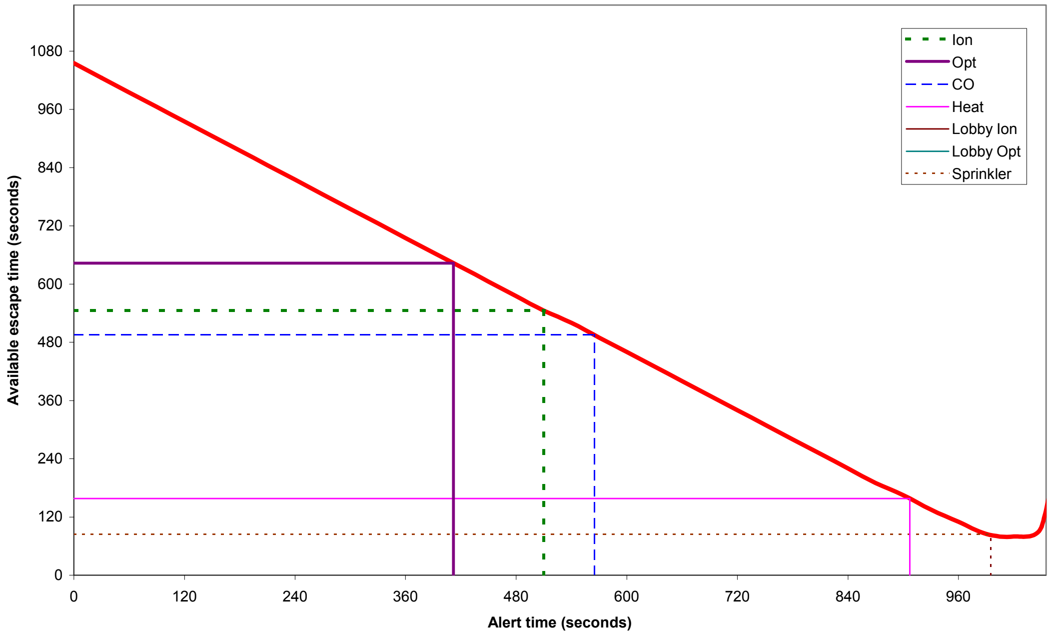

Figure L.1: Test 1 – Alert time versus escape time

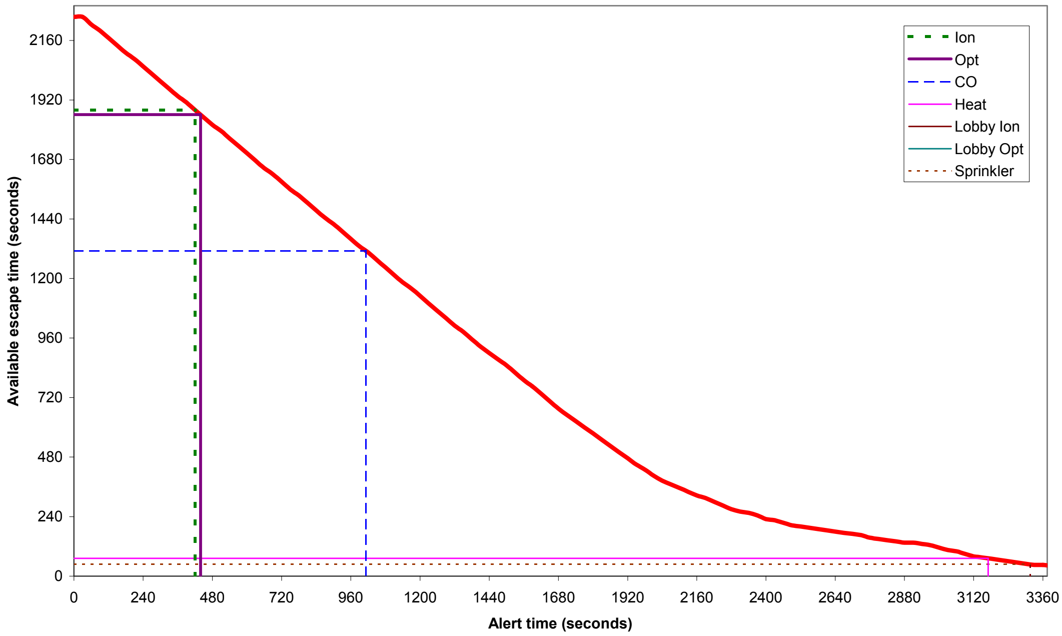

Figure L.2: Test 2 – Alert time versus escape time

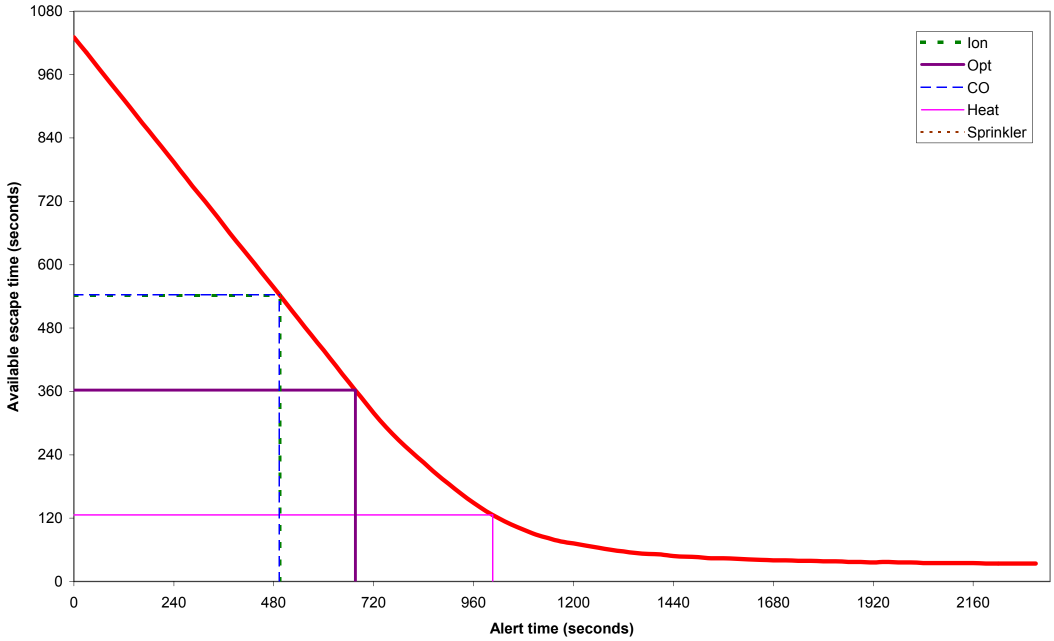

Figure L.3: Test 5 – Alert time versus escape time

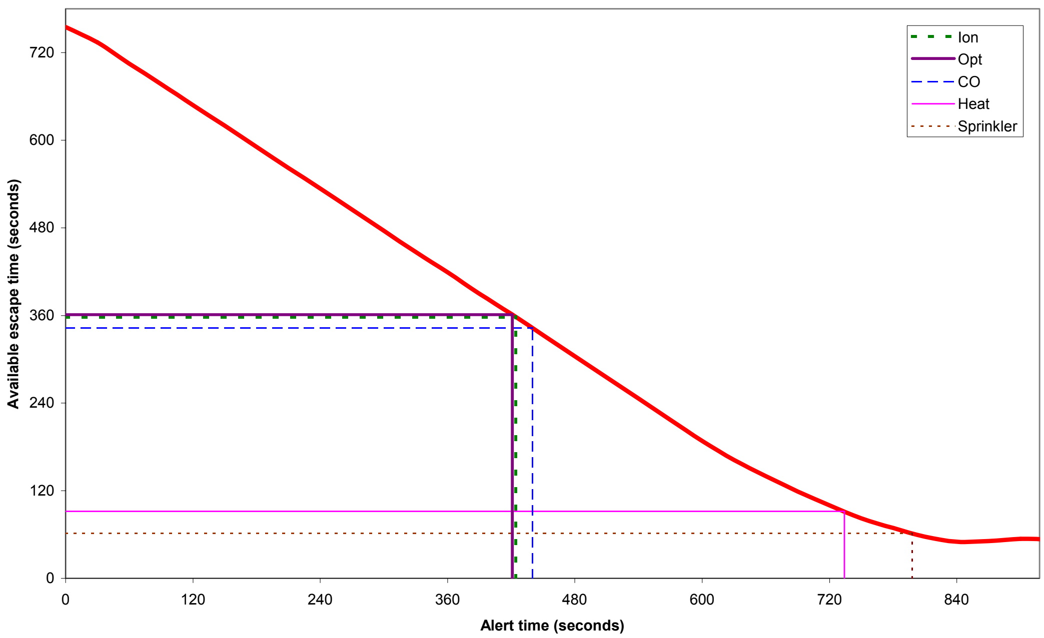

Figure L.4: Test 6 – Alert time versus escape time

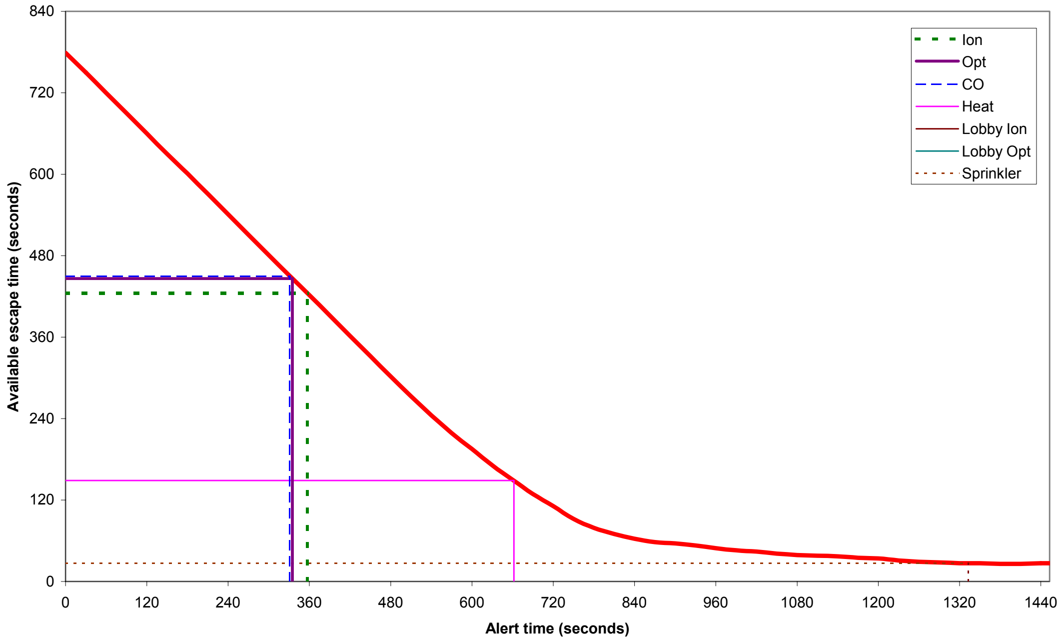

Figure L.5: Test 7 – Alert time versus escape time

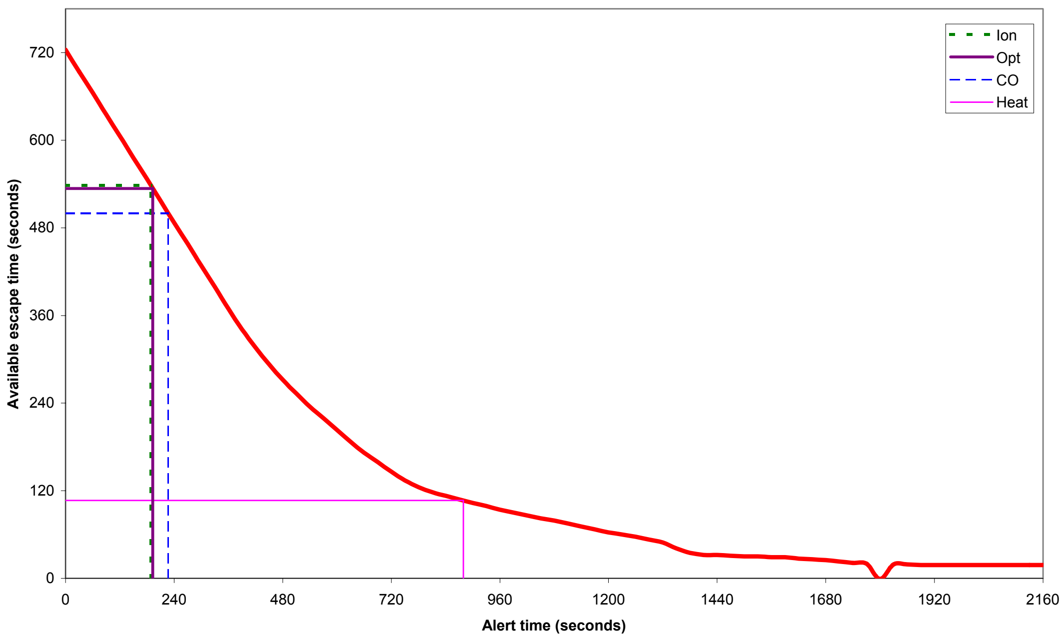

Figure L.6: Test 8 – Alert time versus escape time

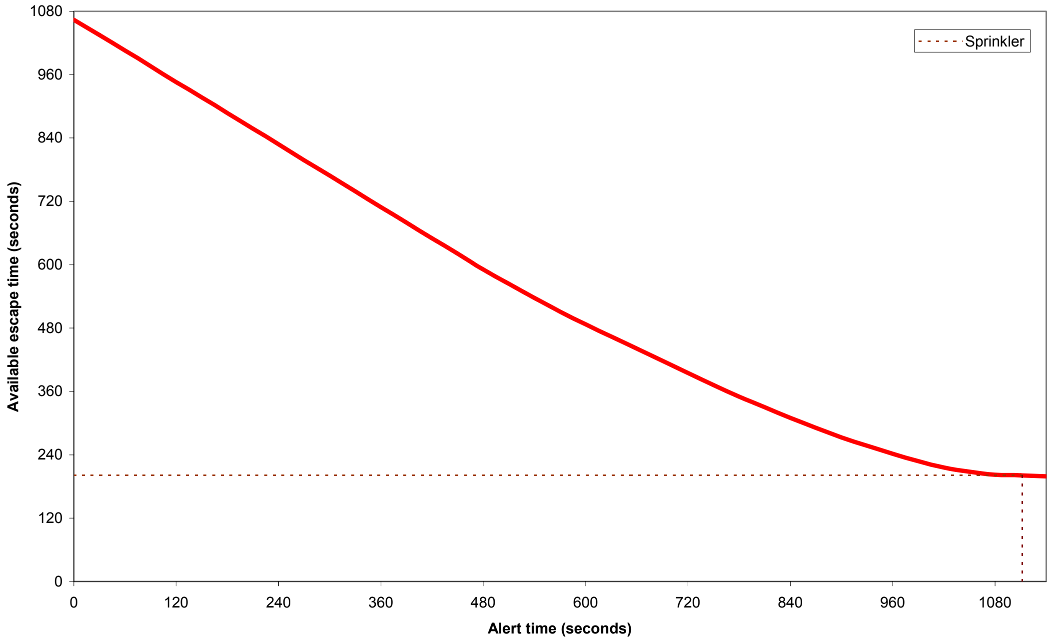

Figure L.7: Test 11 – Alert time versus escape time

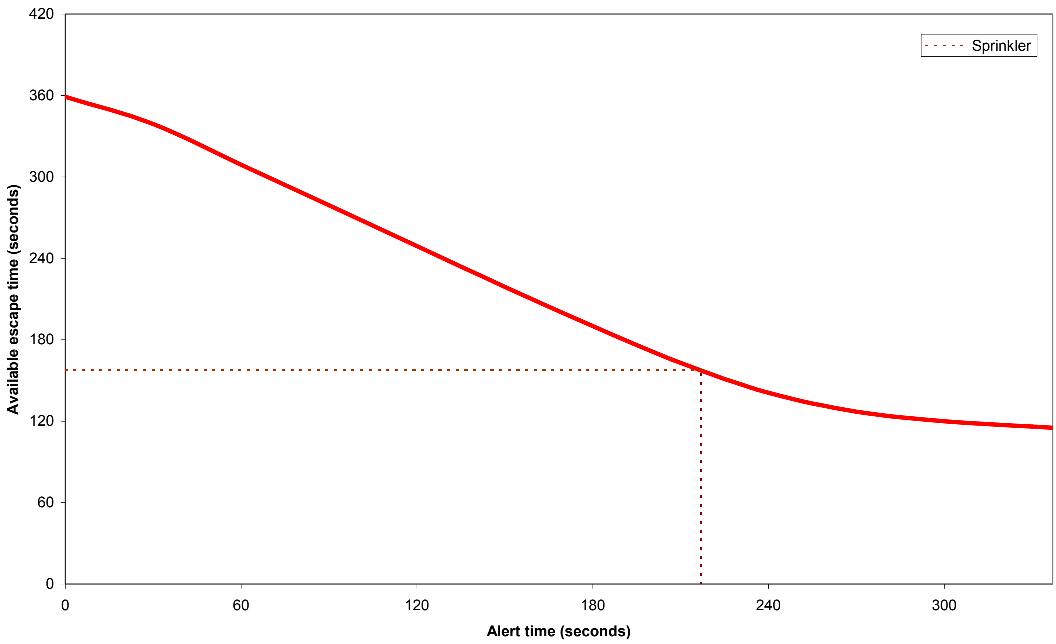

Figure L.8: Test 12 – Alert time versus escape time

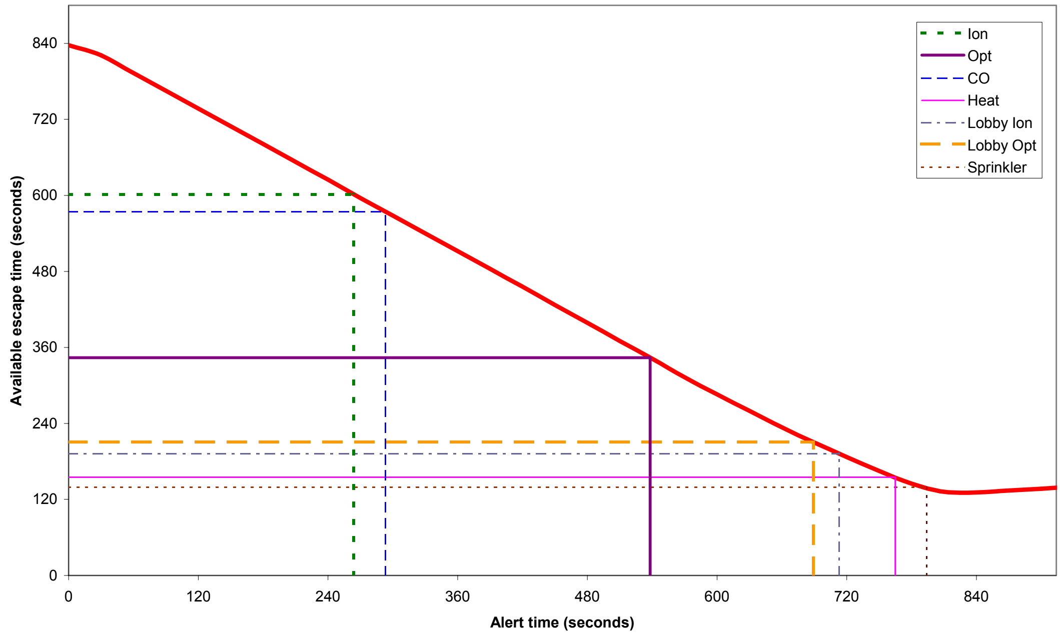

Figure L.9: Test 13 – Alert time versus escape time

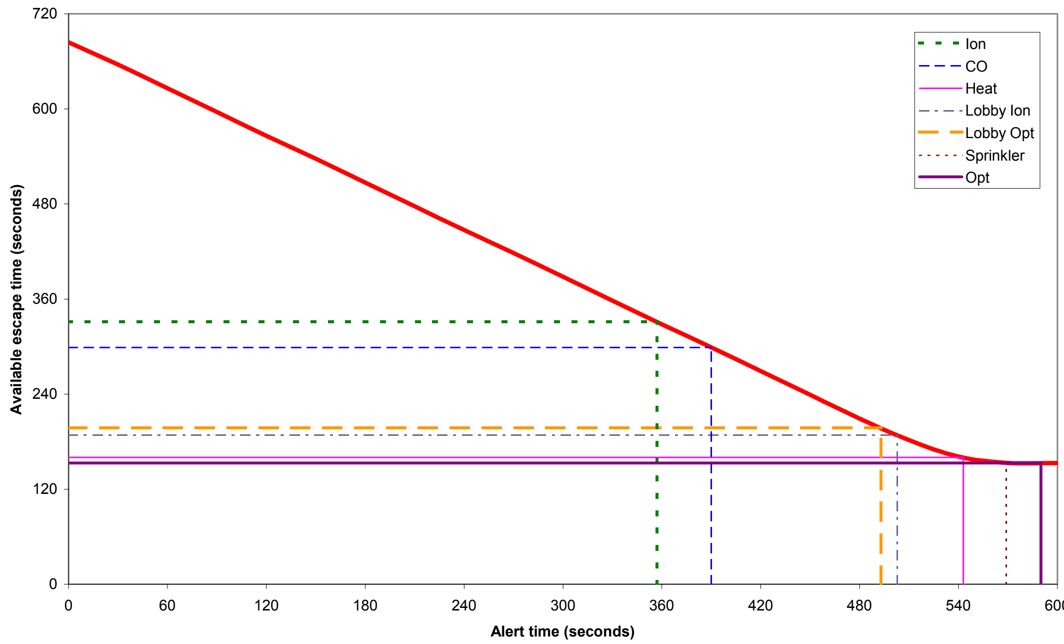

Figure L.10: Test 14 – Alert time versus escape time

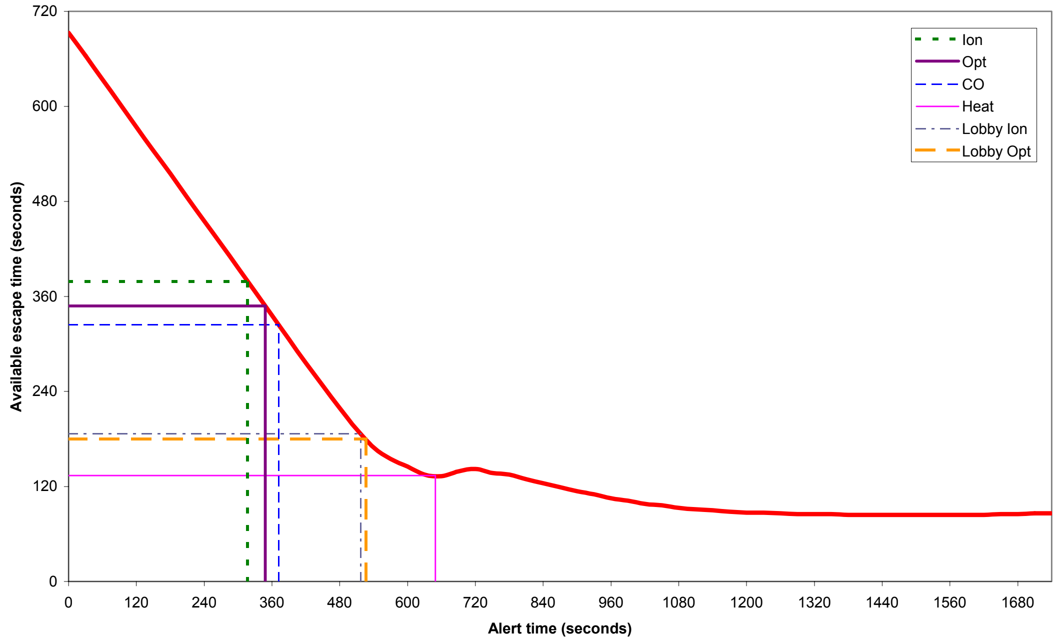

Figure L.11: Test 15 – Alert time versus escape time

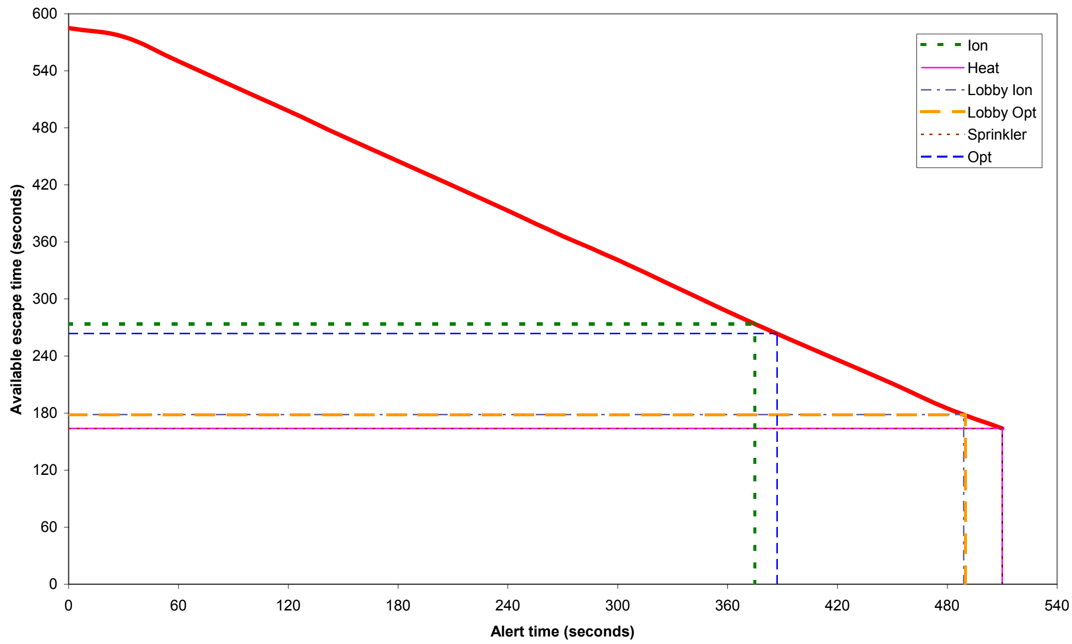

Figure L.12: Test 16 – Alert time versus escape time

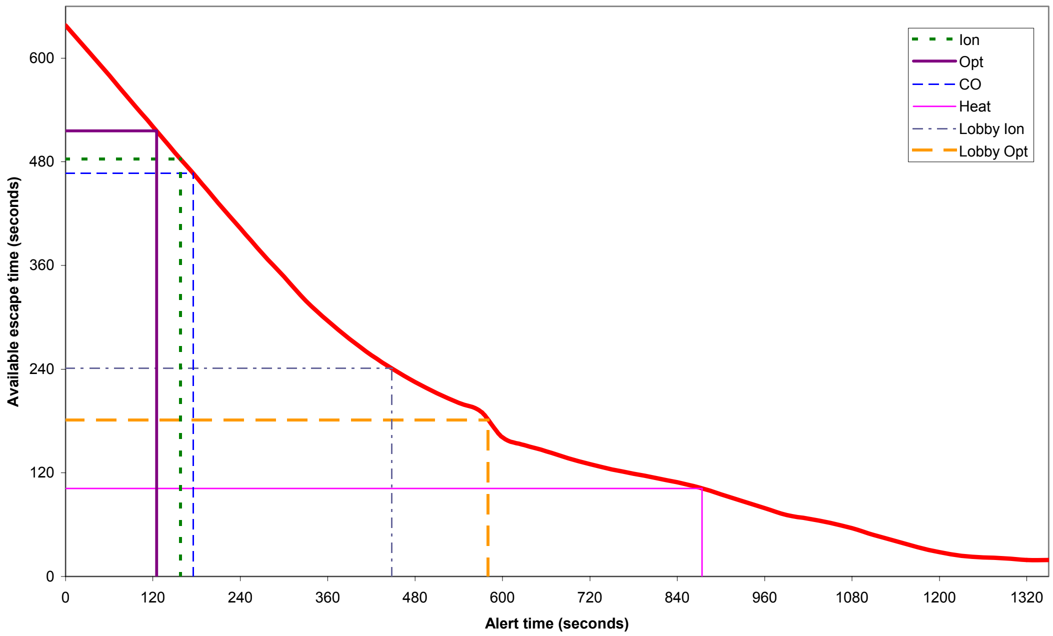

Figure L.13: Test 17 – Alert time versus escape time

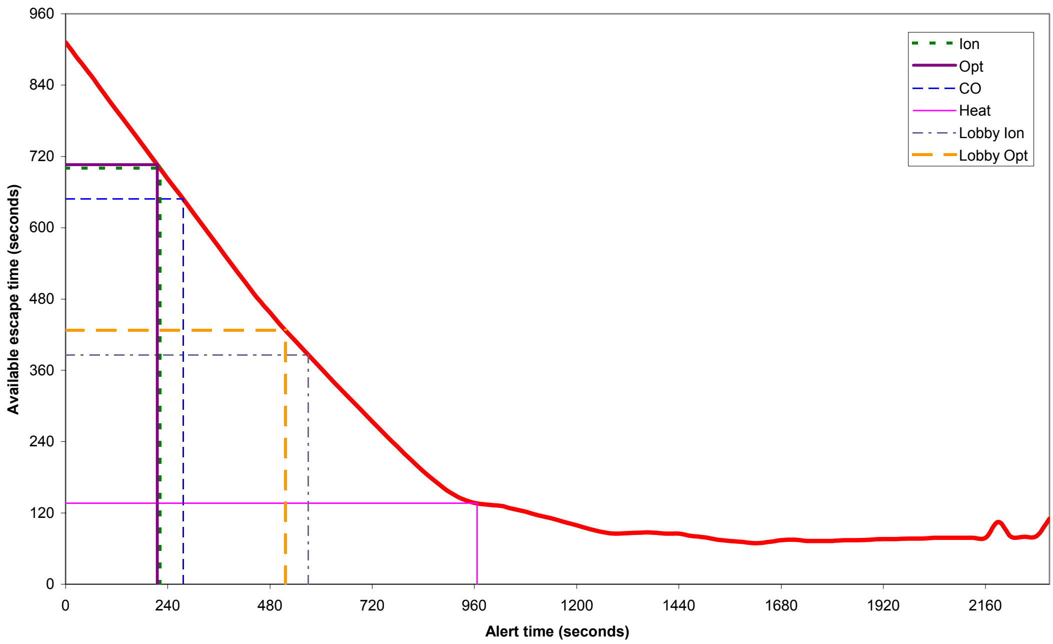

Figure L.14: Test 20 – Alert time versus escape time

Appendix M Event Timelines

Test 1		Test 2		Test 3	
Time	Event	Time	Event	Time	Event
0	Ignition commenced	0	Ignition commenced	0	Ignition commenced
412	Optical detector activates	420	Ionisation detector activates	309	Ionisation detector activates
510	Ionisation detector activates	439	Optical detector activates	313	Optical detector activates
565	CO detector activates	1012	CO detector activates	344	CO detector activates
907	Thermal detector activates	2255	$FED_{asphyxiant}$ threshold exceeded	411	Thermal detector activates
995	Sprinkler activates	3170	Thermal detector activates	437	Sprinkler activates
1055	$FED_{asphyxiant}$ threshold exceeded	3315	Sprinkler activates	557	Sprinkler shut off
1055	Sprinkler shut off	3375	Sprinkler shut off		

Test 4		Test 5		Test 6	
Time	**Event**	**Time**	**Event**	**Time**	**Event**
0	Ignition commenced	0	Ignition commenced	0	Ignition commenced
159	CO detector activates	494	CO detector activates	421	Optical detector activates
164	Ionisation detector activates	495	Ionisation detector activates	424	Ionisation detector activates
174	Optical detector activates	676	Optical detector activates s	440	CO detector activates
247	Thermal detector activates	1006	Thermal detector activates	734	Thermal detector activates
261	Sprinkler activates	1031	$FED_{asphyxiant}$ threshold exceeded	755	$FED_{asphyxiant}$ threshold exceeded
381	Sprinkler shut off	2345	Test terminated	798	Sprinkler activates
				819	Sprinkler shut off

Test 7		Test 8		Test 9	
Time	Event	Time	Event	Time	Event
0	Ignition commenced	0	Ignition commenced	0	Ignition commenced
331	CO detector activates	189	Ionisation detector activates	388	Optical detector activates
335	Optical detector activates	193	Optical detector activates	429	CO detector activates
357	Ionisation detector activates	227	CO detector activates	463	Thermal detector activates
662	Thermal detector activates	724	$FED_{asphyxiant}$ threshold exceeded	477	Sprinkler activates
779	$FED_{asphyxiant}$ threshold exceeded	879	Thermal detector activates	487	FEC_{smoke} threshold exceeded
1333	Sprinkler activates	2202	Test terminated	597	Sprinkler shut off
1453	Sprinkler shut off				

Test 10		Test 11		Test 12	
Time	**Event**	**Time**	**Event**	**Time**	**Event**
0	Ignition commenced	0	Ignition commenced	0	Ignition commenced
434	Sprinkler activates	611	FEC_{smoke} threshold exceeded	217	Sprinkler activates
463	FEC_{smoke} threshold exceeded	1064	$FED_{asphyxiant}$ threshold exceeded	220	FEC_{smoke} threshold exceeded
554	Sprinkler shut off	1112	Sprinkler activates	337	Sprinkler shut off
		1234	Sprinkler shut off	359	$FED_{asphyxiant}$ threshold exceeded

Test 13		Test 14		Test 15	
Time	Event	Time	Event	Time	Event
0	Ignition commenced	0	Ignition commenced	0	Ignition commenced
264	Ionisation detector activates	357	Ionisation detector activates	317	Ionisation detector activates
293	CO detector activates	390	CO detector activates	220	Optical detector activates
538	Optical detector activates	483	FEC_{smoke} threshold exceeded	372	CO detector activates
645	FEC_{smoke} threshold exceeded	493	Lobby optical detector activates	442	FEC_{smoke} threshold exceeded
689	Lobby optical detector activates	503	Lobby ionisation detector activates	517	Lobby ionisation detector activates
713	Lobby ionisation detector activates	543	Thermal detector activates	526	Lobby optical detector activates
765	Thermal detector activates	569	Sprinkler activates	649	Thermal detector activates
794	Sprinkler activates	590	Optical detector activates	693	$FED_{asphyxiant}$ threshold exceeded
837	$FED_{asphyxiant}$ threshold exceeded	684	$FED_{asphyxiant}$ threshold exceeded	1841	Test terminated
914	Sprinkler shut off	689	Sprinkler shut off		

Test 16		Test 17		Test 18	
Time	Event	Time	Event	Time	Event
0	Ignition commenced	0	Ignition commenced	0	Ignition commenced
375	Ionisation detector activates	125	Optical detector activates	317	Optical detector activates
387	Optical detector activates	158	Ionisation detector activates	412	CO detector activates
463	FEC_{smoke} threshold exceeded	175	CO detector activates	528	Lobby optical detector activates
489	Lobby ionisation detector activates	330	FEC_{smoke} threshold exceeded	528	Sprinkler activates
490	Lobby optical detector activates	448	Lobby ionisation detector activates	531	Lobby ionisation detector activates
518	Thermal detector activates	580	Lobby optical detector activates	539	FEC_{smoke} threshold exceeded
518	Sprinkler activates	638	$FED_{asphyxiant}$ threshold exceeded	651	Sprinkler shut off
585	$FED_{asphyxiant}$ threshold exceeded	874	Thermal detector activates		
638	Sprinkler shut off	1379	Test terminated		

Test 19		Test 20		Test 21	
Time	Event	Time	Event	Time	Event
0	Ignition unsuccessful	0	Ignition commenced	0	Ignition commenced
		215	Optical detector activates	171	Ionisation detector activates
		221	Ionisation detector activates	301	CO detector activates
		276	CO detector activates	378	Optical detector activates
		505	FEC_{smoke} threshold exceeded	406	Thermal detector activates
		516	Lobby optical detector activates	427	Sprinkler activates
		570	Lobby ionisation detector activates	446	FEC_{smoke} threshold exceeded
		912	$FED_{asphyxiant}$ threshold exceeded	566	Sprinkler shut off
		966	Thermal detector activates		
		2445	Test terminated		